Development of a rotational shear penetrometer for assessing snowpack stability

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A Thesis Submitted in Fulfilment
of the Requirements for the Degree of
Masters in Mechanical Engineering
in the Department of Mechanical Engineering
University of Canterbury
Christchurch
New Zealand

2005

Abstract

This Master of Engineering thesis describes the development of a portable, multiple-sensor instrument to provide rapid, quantitative snow stability information over the area of an avalanche start zone.

Using a modified geomechanics shear vane an extensive fieldwork programme was carried out with the primary objective of correlating the shear vane against traditional measures of snow shear strength. Numerous shear vane configurations were investigated during the course of this research and their relative effectiveness in predicting snow slope stability was determined.

A prototype shear penetrometer was then developed based on the findings of this study and incorporated sensors to measure snowpack penetration force, temperature and shear strength. Use of a miniature signal transmitter contained within the instrument probe enabled data to be transmitted to a receiver unit and laptop computer at the snow surface. A test rig was also developed, applying the mechanical force required to drive the instrument probe down into the snowpack. The design of this test rig provides the instrument probe with a rotational motion in an axis perpendicular to snowpack layering and a translational motion along this axis with rotational and translational speeds able to be varied independently.

The shear penetrometer was developed to a level where all three system components (the instrument probe, laptop/receiver unit and the test rig) were operational to a degree that field testing could be carried out. Work is to continue within the University of Canterbury on the development of the operator interface, field testing of the prototype instrument and development of new sensor modules.

Acknowledgements

Throughout the duration of this research the expertise, guidance and support of many people was gratefully received and I would like to acknowledge a great debt of gratitude to all those involved. Firstly to my academic supervisor Dr. Keith Alexander, for your patience, advice and design expertise. Your support has been much appreciated.

Thank you to Arthur Tyndall for your enthusiasm and imagination from which this project was started. To all the Mechanical Engineering Department technicians involved in this research, in particular Julian Phillips and the workshop staff, it has been your input that has made this project such a success. Thank you. Many thanks also to the Broken River Ski Field for your assistance throughout this research. The snow safety knowledge provided by your staff has been invaluable.

Finally I would like to thank my friends and family for your continual support. I hope one day I will be able to return the gesture.

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Chapter 1

Introduction

This document outlines the work undertaken on the development of a rotational shear penetrometer to provide rapid, quantitative snow stability information over the area of an avalanche start zone. This work was the topic of a Master of Engineering Degree at the University of Canterbury, New Zealand.

1.1 Trends in Avalanche Incidents

1.1.1 Internationally

Developments in avalanche protective structures and control measures have significantly reduced potential hazards to mountain villages and avalanche affected transportation routes and resulted in a change in the nature of avalanche risk. Increasingly, people are venturing into avalanche terrain in pursuit of winter recreational activities and it is now these areas that represent the greatest hazard and, as a consequence, the greatest proportion of avalanche fatalities. In North America more than three quarters of all avalanche fatalities can be attributed to the recreational activities of skiing, snowboarding, mountaineering and snowmobiling. In Europe this figure is around 85%. Overall these changes have resulted in a dramatic increase in global avalanche fatalities over the past fifty years (McClung and Schaerer, 1993).

1.1.2 New Zealand

On a global scale New Zealand has a relatively low avalanche risk which is largely limited to backcountry mountainous terrain, ski field areas, their access roads and to the Milford Sound highway. There were a total of 37 avalanche related fatalities in New Zealand between 1981 and 1998, with an average of around thirty reported avalanche incidents per year. Of these fatalities 65% consisted of people taking part in the recreational activities of mountaineering, skiing, snowboarding and tramping, with a further 19% being involved in training exercises and 16% being killed in work related activities (Irwin and MacQueen, 1999). Contrary to international trends New Zealand statistics do not show a noticeable increase in the avalanche fatality rate.

New Zealand's club ski fields represent a particularly high avalanche risk, accounting for 5% of all ski field visitor days, while making up 60% of all ski field related avalanche fatalities (Irwin and MacQueen, 1999). Tight financial constraints, leading to under-resourcing, combined with intense public pressure to open the ski field following fresh snowfalls make these areas highly susceptible to poor snow safety decisions.

1.2 The Avalanche Enigma

Avalanche formation is an extremely complex process, driven predominantly by prevailing meteorological conditions but also affected by subtle changes in terrain topography and the physical and mechanical properties of alpine snow. As a result of the diverse interactions of these variables avalanche hazard forecasting has remained a largely intuitive exercise, incorporating an assessment of meteorological observations, snowpack profiles and slope stability tests.

This evaluation procedure, although very rarely resulting in complete failure, relies on varied and often redundant sources of information and mistakes are common, even for the experienced avalanche forecaster. The greatest difficulties arise due to the huge volume of information obtained and the tremendous amount of experience required to accurately assimilate what information is important in assessing snow slope stability and what is not.

The most useful snow stability information, that provided by stability tests, is also the most time consuming and dangerous to obtain. Typically such tests require the digging of a snow pit, which in itself can take up to an hour to dig. Further difficulties arise from the extreme spatial variation in snow cover distribution and in the changes in snow crystal structure (snow metamorphism) over time.

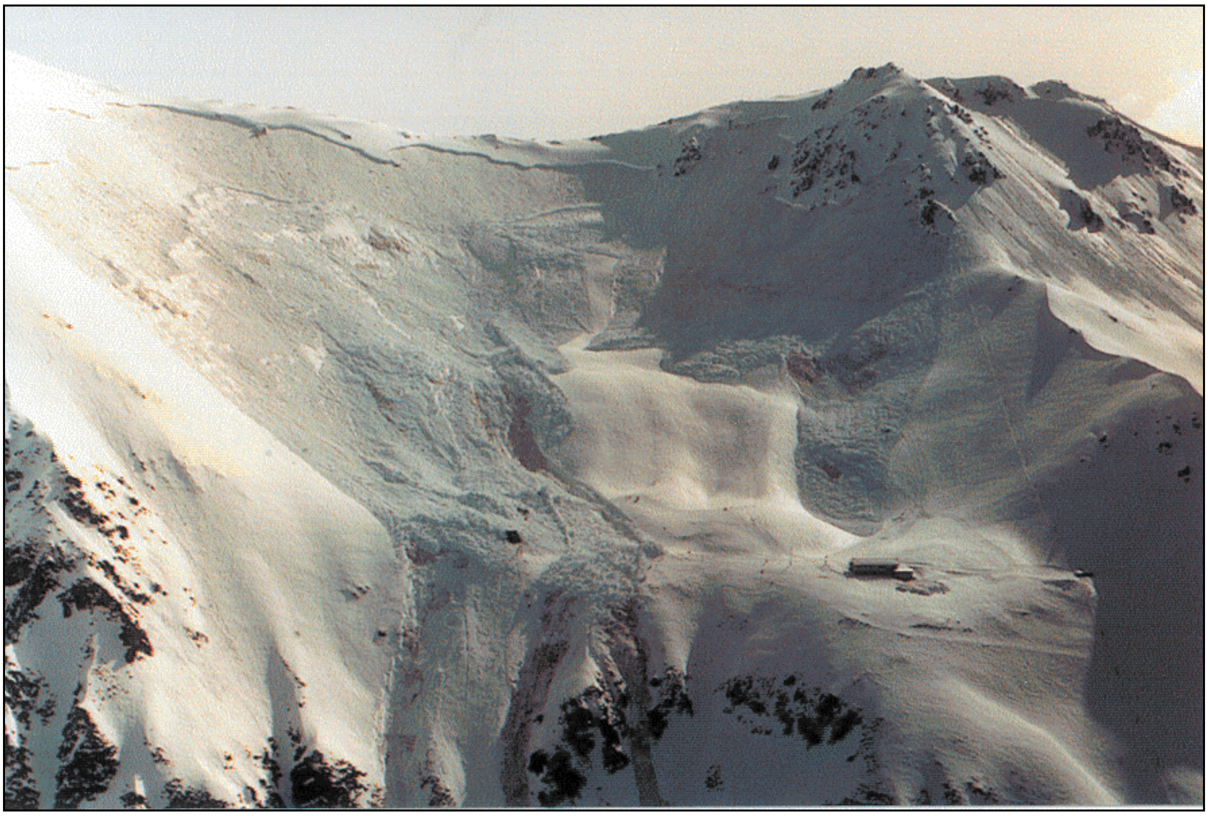


Figure 1.1: Large Slab Avalanche, Broken River Ski Field, Craigieburn Range.

1.3 Project's Background

Arthur Tyndall, former president of the Broken River ski field, has been interested in avalanche prediction and prevention for many years, having witnessed the devastating effects first-hand. One such event was the large slab avalanche shown in Figure 1.1, which occurred at Broken River in August 1992. This avalanche fractured across the entire area of the main ski basin while the field was open for operation resulting in one fatality.

Following this avalanche Arthur undertook a professional avalanche management training course and became aware that simple measurements he would have undertaken as a civil engineer were not being used in snow stability evaluation. He therefore set about modifying instrumentation normally used for soil sampling to use with snow.

It is generally agreed amongst the snow science community that the mechanism of slab avalanche release involves an initial shear failure. The focus of this work has therefore centred around the measurement of shear strength within the seasonal snowpack. For this purpose the shear vane, as illustrated in *Figure 1.2*, was developed. Inserted from the snow surface at a direction perpendicular to snow layering, this instrument provides a quantitative measure of the torque required to cause the rotational shear failure of an isolated snow column.

This concept was conveyed to the Mechanical Engineering Department at the University of Canterbury from which this project was initiated.

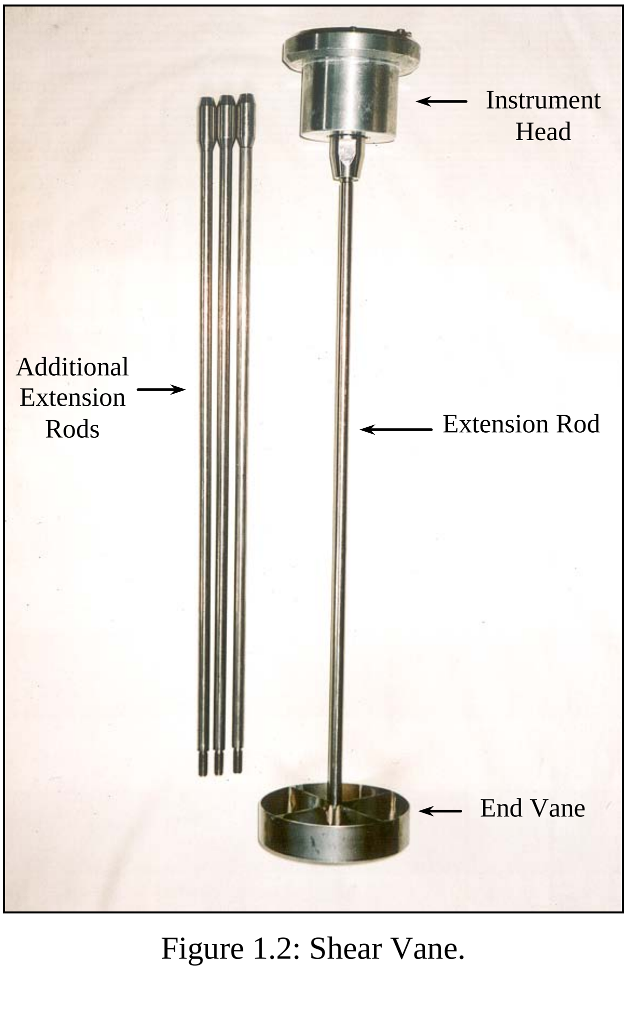


Figure 1.2: Shear Vane.

1.4 Scope of Master's Thesis

The aim of this Master's thesis was to develop a portable instrument to be used by snow safety professionals to assist in assessing snow slope stability. The scope of this research therefore included an extensive fieldwork programme investigating the characteristics of the shear vane, leading ultimately to the design and fabrication of a first prototype shear penetrometer.

1.5 Outline of this Document

Chapter 2 provides a brief background to snow slope failure mechanisms, avalanche formation processes and current snow stability evaluation methods. The concept of the shear vane, its operation and mechanics, is then described in *Chapter 3*, along with results from an initial field study. An extensive field investigation, carried out on a modified shear vane, is reported in *Chapter 4*, with the developed shear penetrometer presented in *Chapter 5*.

Chapter 2

Avalanche Phenomena

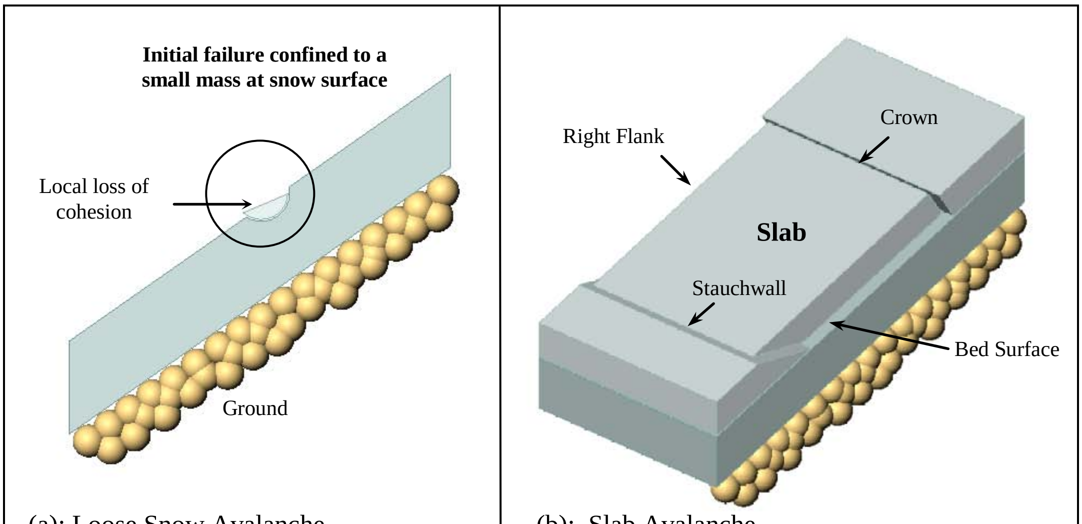
This chapter provides an introduction to the processes responsible for the development of instabilities within the snowpack and the mechanisms of snow avalanche release. Current methods of snow stability evaluation are also presented.

Perla and Martinelli (1976) and McClung and Schaerer (1993) both provide comprehensive reviews of avalanche technology and unless specifically stated the information contained in this chapter is derived from these publications.

2.1 Mechanism of Snow Slope Failure

In a snowpack homogeneous snow exists in layers originating from periods of uniform snowfall. Individual layers can have vastly different physical and mechanical properties, dependent largely on the meteorological conditions at the time of deposition and the subsequent changes in snow crystal form. Avalanche formation is highly dependent on the properties of these individual layers, with snow failure occurring;

- Within a weak snow layer as a result of poor cohesion between grains,
- At a weak interface between two layers due to poor bonding between layers,
- At the interface between the snow and the underlying substratum.



(a): Loose Snow Avalanche. (b): Slab Avalanche.

Figure 2.1: Mechanism of Snow Slope Failure.

In unstable snow conditions there is a fine balance between snowpack strength (bonding forces between snow grains) and the stress placed on the snowpack (component of it's own weight acting in a down-slope direction). As a result of spatial variability in both snow mechanical properties and snow loading distribution, regions of relatively high strength (pinning zones) and regions where local stresses exceed strength (deficit zones) are formed. Application of further stress or a continued reduction in snowpack strength results in an increase in deficit zone size, until a critical size is reached and failure occurs. For such a failure to occur there must be;

- A closely balanced stress-strength relationship in the snowpack.
- A trigger which upsets this balance. This can include new snowfall, wind deposited snow, a rise in temperature, ice fall, earthquake, skier, snowboarder, machinery and explosives.
- A mechanical condition that allows the fracture to propagate.

2.1.1 Loose Snow Avalanche

For snow with very little cohesive strength this initial failure is confined to a small mass of surface snow with progressive failures resulting in the release of a loose snow avalanche, as shown in *Figure 2.1(a).* These avalanches start from a single area or point, spreading out in a triangular pattern as they move down the slope, entraining more snow as they descend. Loose snow avalanches typically occur in new snow before bonding has had sufficient time to give strength to the snowpack or in wet snowpacks where intergranular bonds have lost cohesion due to melting.

Dry, loose snow avalanches are usually less destructive than slab avalanches, involving smaller volumes of lower density snow. They are therefore considered not as dangerous and often serve to gradually redistribute freshly fallen snow to slopes of a gentler gradient.

Wet, loose snow avalanches are usually triggered by heavy melt due to warming by the sun or because of rainfall increasing the water content of the near-surface snow. Because of the large amount of free water present, and hence very high density, these avalanches can be very destructive, running long distances on gentle slopes.

2.1.2 Slab Avalanche

Slab avalanches occur when a weak layer, or a weak layer interface, fails beneath a relatively cohesive snow layer. In this case the formation of a deficit zone causes a breakdown of the bonds attaching the snow slab to the bed surface and upon reaching critical size a rapid increase in tensile stress is applied to the crown region, causing catastrophic, brittle fracture. This results in a block of snow, often several meters deep, releasing as one slab and is easily identified by a well-defined fracture line in the crown and flank regions of the avalanche, as depicted in *Figure 2.1(b).*

2.2 Diversity in Snow Crystal Forms

Up to 80 different categories of snow crystal forms have been identified, each with its own unique physical and mechanical properties. This diversity is one of the major difficulties in snow stability work, compounded even further by a continual change in predominant snow crystal type produced throughout the duration of a storm cycle.

2.2.1 Atmospheric Snow Crystal Formation

The basic crystal form is determined by the direct vapour transfer of water vapour molecules onto an ice crystal, as illustrated in *Figure 2.2(a)*. With this mechanism ice crystal growth occurrs in two basic directions: in the basal plane of the ice crystal or perpendicular to it in the longitudinal growth direction. Four basic crystal forms are commonly produced by this process with the exact crystal shape being determined by the temperature and vapour pressure the crystal goes through in its formation. These four basic crystal forms are;

- Stellar — Six - branched star
- Plate — Hexagonal flat plate
- Column — Six - sided hollow or full column
- Needle — Long, fine crystal

The second growth mechanism occurs as the crystals move in the atmosphere. Falling as they gain in size, the ice crystals collide with water droplets, which freeze onto the crystals surface in a process called *riming*, shown in *Figure 2.2(b)*. When riming entirely fills the branches of an ice crystal, a rounded crystal form called *graupel*, infamous for its poor bonding strength, is produced.

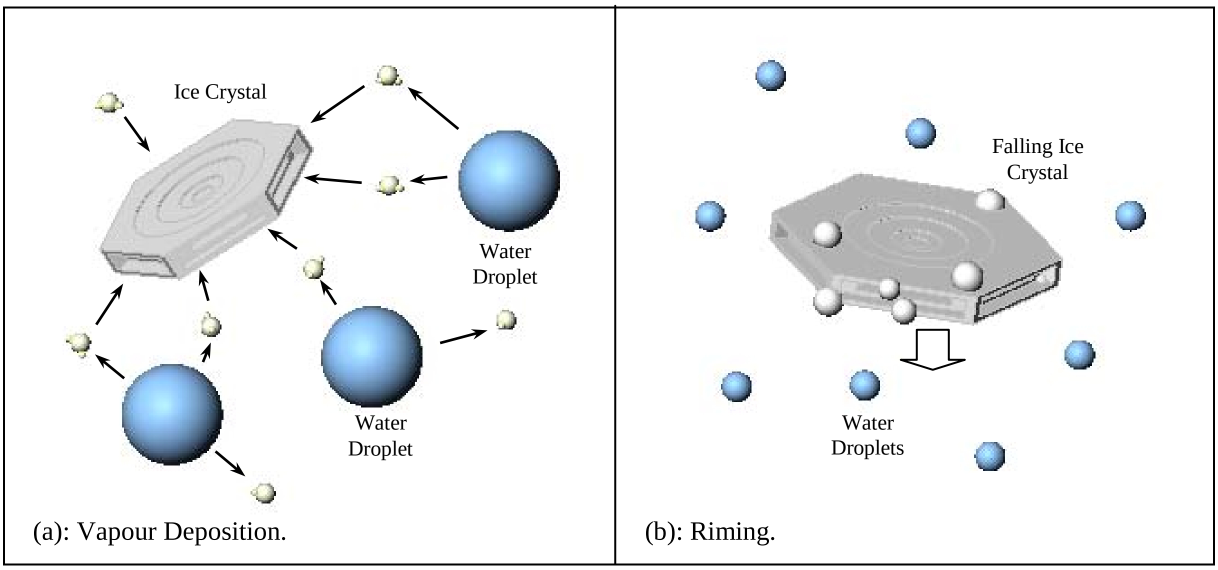


Figure 2.2: Ice Crystal Growth Mechanisms.

The combined effect of direct vapour transfer and riming processes is to produce an extremely diverse range of ice crystal configurations. This diversity in ice crystal geometric configurations produces an equally diverse range of physical and mechanical properties, compounding the avalanche forecasting problem.

2.2.2 Surface Hoar Formation

Surface hoar forms on cold, calm nights where loss of long-wave radiation from the snowpack causes very low temperatures and humidity at the snow surface. Surrounded by relatively warm, moist air, a vapour transfer occurs between the air and the snow resulting in the formation of long feathery hoar crystals. Prolonged periods of fine weather enables these crystals to grow over consecutive nights, or even weeks, resulting in crystals up to 100mm in length.

Surface hoar forms an extremely important part in avalanche release as buried hoar layers provide a very slick surface for overlying snow layers to slide on. Typically compressed to several millimetres in thickness, detection of surface hoar in the snowpack can be difficult, a problem further exacerbated when buried surface hoar crystals collapse to lie parallel to the snow surface. In this situation visual observation of a snowpack profile will not always reveal the presence of these crystals.

2.3 Snow Metamorphism

Once deposited on the surface of the snowpack new snow crystals begin a process in which they change in size, shape, as well as physical and mechanical properties under the influences of three metamorphic processes: rounding, faceting and melt-freeze metamorphism. Metamorphism of snow is the result of sublimation and deposition, in which water molecules are removed from one snow grain and added to another, resulting in a structural change to both crystals. This process of sublimation and deposition occurs by two mechanisms where;

- Vapour moves from warmer surfaces to colder surfaces.
- Vapour moves from convex surfaces to concave surfaces.

In most circumstances the seasonal snowpack is bounded by the atmosphere above and the ground surface below. Stored heat in the ground from summer warming and geothermal heat from the earth's centre combine to warm the basal snow layer to around 0°C. The surface, on the other hand, is subjected to extremes in temperature due to diurnal fluctuations and synoptic weather conditions, resulting in a temperature difference, often as much as 20°C between the surface snow and the basal snow layer. It is this temperature gradient that largely determines the predominant vapour transfer mechanism, and hence type of metamorphic process to take place in the snowpack. Where large temperature gradients exist, flow from warmer surfaces to colder surfaces dominates. Where small temperature gradients exist, flow from convex surfaces to concave surfaces dominates. A temperature gradient of 10°C/m forms the boundary about which the two mechanisms operate.

2.3.1 Rounding Metamorphism (Equi-Temperature Metamorphism)

Due to very low water vapour pressures in the snowpack, relative to the supersaturated atmosphere in which ice crystals are produced, new snow crystals are thermodynamically unstable. Crystals with the largest surface area to volume ratios experience the greatest instabilities and are therefore the first to breakdown into smaller, more rounded crystals. This process occurs over several days and results in the initial consolidation and settlement of the snowpack following a fresh snowfall.

If temperature gradients remain low, rounding of these snow grains continues with water vapour transfer occurring from the sharp convex regions of the ice crystal to the concave regions between crystal branches, as shown in *Figure 2.3*. Large grains grow in size at the expense of smaller ones, resulting in more or less rounded grains of uniform size. High snowpack temperatures (-5°C - 0°C) promote rapid rounding rates.

Concave regions also appear at the contact points between rounded grains with vapour transfer forming strong intergranular bonds in a process called *sintering*, as illustrated in *Figure 2.4(a)*. This process results in a highly stable snowpack.

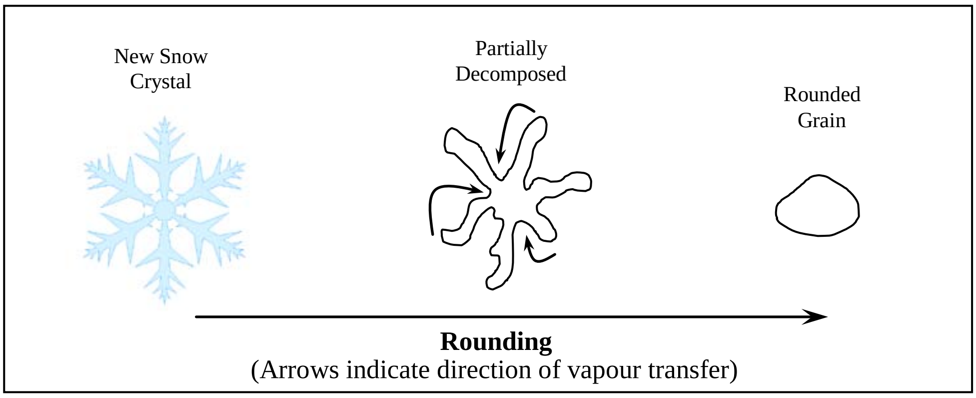


Figure 2.3: Rounding Metamorphism.

2.3.2 Faceting Metamorphism (Temperature Gradient Metamorphism)

Large temperature gradients result in the predominant vapour transfer of water molecules from warmer to colder surfaces. As these large temperature gradients (greater than 10°C/m) only occur when the snow surface is significantly colder than the basal snow layer, movement of water vapour is upwards in the snowpack. Molecules sublimate off the top surface of one snow grain and are deposited on the lower surface of a grain above it, resulting in the formation of facets. These faceted snow grains are angular in shape, with flat faces and form persistent weak layers within the snowpack.

Continued faceting results in the formation of hexagonal cup-shaped crystals known as *Depth Hoar,* which forms deep in the snowpack. This deep change in snowpack structure is the result of lower level warming which maintains a basal snow layer at about 0°C. As vapour transfer, and hence crystal growth rates are determined by temperature, only the lower layers are warm enough in a large temperature gradient snowpack to allow any significant metamorphism process to occur.

This formation of depth hoar causes a loss of bonding between snow grains, as illustrated in *Figure 2.4(b),* resulting in very weak snow. Depth hoar crystals are also very durable and once formed, are likely to be present in the snowpack for the remainder of the season.

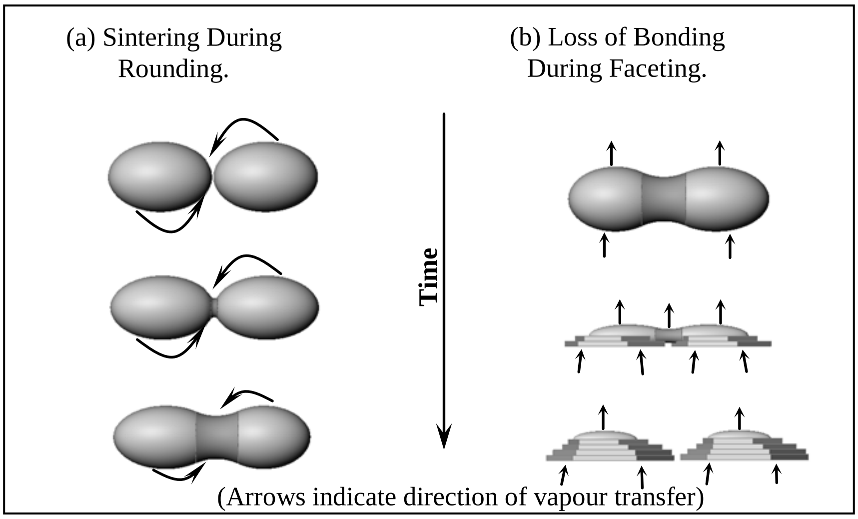


Figure 2.4: Metamorphic Effect on Bonding in Dry Snow.

2.3.3 Melt-Freeze Metamorphism

The metamorphism of wet snow is known as *melt-freeze metamorphism* because it is the result of melting and refreezing of the liquid water between snow grains. During the melting cycle, liquid water from rain, fog or melt-water resulting from warm air temperatures, causes a breakdown in the bonds between grains. This drastically reduces the strength of the snowpack but this strength returns upon refreezing resulting in a very stable snowpack. Liquid water, which percolates through the snow layers, may further reduce stability by forming lubricating water films or ice lenses.

2.4 Important Influences on Avalanche Formation

Snow stability evaluation provides a comparative assessment between the strength of individual snow layers and the stresses placed on them by the weight of overlying snow. The main variations in layer properties are a direct result of the snow crystal diversity and metamorphic processes discussed in the previous two sections. There are however many other factors affecting snow stability with some of the most significant contributors discussed below.

2.4.1 Temperature

As snow exists in a state very close to its melting point, any temperature change will have a dramatic effect on its strength properties. Wind, precipitation, fog, cloud cover, geothermal warming and solar radiation all act to influence snowpack temperatures, the main effects being summarised below, with (+) indicating a positive effect on stability, whereas (–) indicates a negative effect.

High Snowpack Temperature

- \- Melting of grain bonds,
- \+ Rapid metamorphic rate (Rounding),
- \- Lubrication of sliding layers,
- \+ Low temperature gradient (Rounding and melt-freeze metamorphism dominant).

Low Snowpack Temperature

- \+ Freezing of grain bonds and free liquid water,
- \+ Slow metamorphic rate (Faceting),
- \- Surface hoar formation,
- \- Slow decomposition of new snow crystals,
- \- High temperature gradient (Faceting metamorphism dominant).

2.4.2 Wind

Wind speed and direction plays a major role in avalanche formation. It is responsible for the spatial distribution of snow cover due to the redistribution of settled snow layers, as well as the decomposition of freshly fallen snow crystals and the formation of *wind slab*. These effects, combined with consecutive storms acting in different directions, can produce complex three-dimensional layering patterns, the stability of which is highly varied and very difficult to deduce.

Snow Redistribution

Snow is transported from regions of high wind velocity and deposited, as the wind decelerates, on the leeward side of terrain features. The snow layer variation produced by this effect is phenomenal with even light winds providing sufficient snow redistribution, to allow the accumulation of large deposits in a relatively short period of time. This results in a rapid development of instability.

Snow Decomposition

New snow consists of fragile ice crystals which break apart in continued wind-induced collisions with the snow surface. These small fragments, upon deposition, pack tightly together and rapid bond formation takes place. Due to this mechanism cohesive slabs are quickly produced, usually in leeward areas already heavily loaded with redistributed snow.

Wind Slab

Wind slab is a hardened layer, formed by the action of wind blowing across the snow surface, on which further snowfalls can slide.

2.4.3 Precipitation

Precipitation type and rate is important for avalanche formation as it acts to add weight to the snowpack, thereby increasing the stress placed on weaker layers. At high precipitation rates, loading occurs at a rate faster than the new snow gains strength therefore resulting in decreasing stability.

Maritime snow climates, typical of island nations such as New Zealand and coastal mountain ranges such as the Cascade Range in the western United States, experience the possibility of rain falling at any time during the winter. This causes rapid development of instability with the addition of a large amount of stress, combined with the reduction in strength caused by the melting of grain bonds and the lubrication of potential sliding surfaces.

2.4.4 Other Meteorological and Snowpack Influences

There are many meteorological and snowpack factors which affect snow slope stability. Their effect is generally an interactive influence of a wide range of variables and the exact cause of instability is usually difficult to determine. A list of some of these parameters is provided in *Section 2.5.1.*

2.4.5 Terrain Influences

Slope Angle

Hazardous avalanches occur most frequently on slopes of 30° - 45°, with slopes steeper than 45° having frequent, small avalanches. Slopes steeper than 60° generally do not produce avalanches as snow continuously sloughs off them, while avalanches are also very rare on slopes less than 25°.

Slope Aspect and Elevation

Slope aspect determines the exposure of a slope to wind and solar radiation while snowfall, temperature and wind speed and direction all vary with elevation.

Ground Roughness

Irregularities of the ground surface such as trees, boulders or logs will usually anchor the snowpack until it is deep enough to form a smooth surface. The threshold snow depth is approximately 30cm for smooth ground, 60cm on average mountain terrain and 120cm on very rough ground. This ground roughness principle forms the basis of many of the protective structures built in avalanche start zones.

Stress Concentrators

Certain terrain features produce stress concentrations thereby reducing the applied load that can be added before an avalanche will occur. Such starting points include;

- Rock outcrops
- Trees
- Cornice
- Cliff bands
- Convex slopes

2.5 Present Snow Stability Evaluation Methods

2.5.1 Overview

Snow stability evaluation has changed very little over the past half century and combines a mix of deterministic treatment of snow and weather parameters and inductive logic to reach actual forecast decisions (La Chapelle, 1980). The present method of snow stability evaluation is summarised as;

1. All available data about the slope and area in question is collected. The relevance and ease of interpretation of this collected data varies widely and may consist of vague, anecdotal evidence combined with precise measured values.
2. An initial hypothesis about snow stability is formed.
3. Through snow profile analysis and stability tests this hypothesis is tested.
4. On the basis of these observations the hypothesis is confirmed or revised.
5. An evaluation of slope stability is made and future stability is forecast.

Central to this method is the experience of the avalanche forecaster who must collect, analyse and integrate a series of contributory factors. These factors are used to develop conclusions about the presence, strength and loading of weak layers and are often correlated directly with snow stability through empirically developed relationships. These factors have been stratified into the following three classes based on their ease of interpretation and relevance to avalanche formation.

Class I: Stability Factors. Provide a direct relationship between stress on weak layers.

* Observations of natural avalanche release.
* Results of slope tests including; test skiing, application of explosives, Rutschblock test, shovel shear test and shear frame test.

Class II: Snowpack Factors. Provides evidence about the presence, strength and loading of weak snow layers.

* Snowpack temperatures
* Snowpack structure
* Snow penetrability
* Evidence of past avalanche activity
* Slope use

Class III: Meteorological Factors. Provides indirect evidence about snow stability.

* Precipitation type and intensity
* Wind speed and direction
* Air temperature history
* Humidity history
* Solar radiation

2.5.2 Snow Profile Analysis

Snow profile analysis forms the bulk of the information used to derive a snow stability evaluation and provides a record of snow cover stratigraphy and the characteristics of individual snow layers. The objectives of snow profile analysis being to;

- Identify the snow layers that make up the snowpack,
- Identify weak bonds between layers and to determine their strength,
- Observe snowpack temperatures and temperature gradients,
- Monitor and confirm changes in snowpack stability,
- Determine the thickness of a potential slab avalanche.

Snow profile analysis performed during the course of this research was carried out according to the *New Zealand Guidelines and Recording Standards for Weather, Snowpack and Avalanche Observations* (New Zealand Mountain Safety Council, 2000). Throughout these assessments the shovel shear test was used as the primary tool for locating weak layers or weak layer interfaces due to its simplicity, speed and, with practice, reliability.

2.5.3 Shear Frame Test

Researchers and snow practitioners have developed numerous methods for in-situ shear strength measurements of weak layers or weak layer interfaces within the snowpack. These tests include the shear frame, rutschblock, stuffblock and shovel shear tests (Perla and Martinelli, 1976; McClung and Schaerer, 1993; New Zealand Mountain Safety Council, 2000). Of these tests only the shear frame test has been used to measure quantitative shear strength information with analysis being used to derive the stability index; the ratio of the shear strength of a buried weak layer to the shear stress imposed by the weight of the overlying snow layers (Conway and Abrahamson, 1984; Sommerfeld, 1984; McClung and Schaerer, 1993). The use of the shear frame test is illustrated in *Figure 2.5*, in this instance incorporating a frame of 100cm^2 cross sectional area and a height of 25mm.

Figure 2.5: Shear Frame Test.

With widespread use over the past twenty years, in both research and practical applications, the shear frame test has been refined by evaluating the effects of loading rate, normal load and developing correction factors to take into account shear frame size effects (Perla et al., 1982; Perla and Beck, 1983). It does however have several disadvantages including;

- Being a time-consuming task requiring the excavation of a snow pit,
- Shear strength measured without influence of overburden snow,
- Not applicable when weak layer is overlain by very hard snow,
- Large amount of experience required to produce reliable data,
- Due to time-consuming nature of test, spatial variation in shear strength is not usually measured. This allows the potential for collected data to be confined to a "deficit zone" of disproportionately low shear strength or a "pinning zone" in which measurements indicate false snowpack stability.

Because of its use as a quantitative test the shear frame test was used during this research as the standard reference for comparison with the newly developed instrumentation. The procedure for carrying out shear frame tests documented in the New Zealand standard (New Zealand Mountain Safety Council, 2000), fails to take into account testing on an inclined slope and hence the test used throughout this research was based on other published procedures (Perla and Martinelli, 1976; Sommerfeld, 1984; McClung and Schaerer, 1993).

Calculation of the snowpack shear strength was therefore performed according to *Equation (2.1)* below, which describes the shear strength as being the sum of the slope parallel forces divided by the area over which this shear force occurs.

$$\tau_{Shear\,Frame} = \frac{F - g(\rho \times Volume_{Shear\,Frame} + Mass_{Shear\,Frame})\sin\theta}{Area_{Shear\,Frame}} \tag{2.1}$$

Where;

F = Maximum force required to cause failure of the snow sample,
g = Acceleration due to gravity,
ρ = Snow density of failure layer,
θ = Slope angle.

Chapter 3

Shear Vane

This chapter provides an introduction to the shear vane, how it is operated and an analysis of its mechanics. Potential advantages of the device as a surface operated instrument are discussed and an initial field investigation reported on.

3.1 Prototype Device

The manual shear vane proposed by Arthur Tyndall is very similar in nature to the shear frame. Like the shear frame it works by isolating a volume of snow above a weak layer, thereby negating the effect of the surrounding snow. This results in the applied force acting solely through the weak basal layer. The main difference being that the shear vane applies a torque to the snow sample resulting in a rotational shear failure, whereas shear frame measurements involve a translational force application and failure.

The shear vane consists of an instrument head, extension rods and an end vane, as illustrated in *Figure 1.2*. With the end vane inserted into the snowpack the gauge is operated by rotating the instrument head, thereby creating a torque, which is transmitted through a torsion spring to the extension rods and end vane. Further rotation of the instrument head increases the applied torque until shear failure of the snow sample occurs. The maximum value obtained on the dial gauge just prior to failure is used to calculate the shear strength of the snow sample.

Extension rods are in 500mm lengths and can be joined together to provide a combined length of up to two meters, thus enabling the measurement of snow layers deep in the snowpack. They can also be unscrewed from the instrument head and end vane so as to enable portability of the device. Fabricated from aluminium with 4 stainless steel extension rods and end vane the device is very robust and relatively lightweight at 2.4 kg.

3.2 Mechanics

Shear vanes used in geomechanics applications have been theoretically analysed with the determination of *Equation (3.1)*, where r_o, r_i and h are the vane dimensions illustrated in *Figure 3.1.* (Calding and Odenstad, 1950; Craig, 1995; Barnes, 2000).

$$T_{\max} = \tau_{ShearVane}\left[(2\pi r_o h)r_o + 2\left(\pi r_o^2 - \pi r_i^2\right)\left(r_i + \frac{2}{3}(r_o - r_i)\right)\right] \tag{3.1}$$

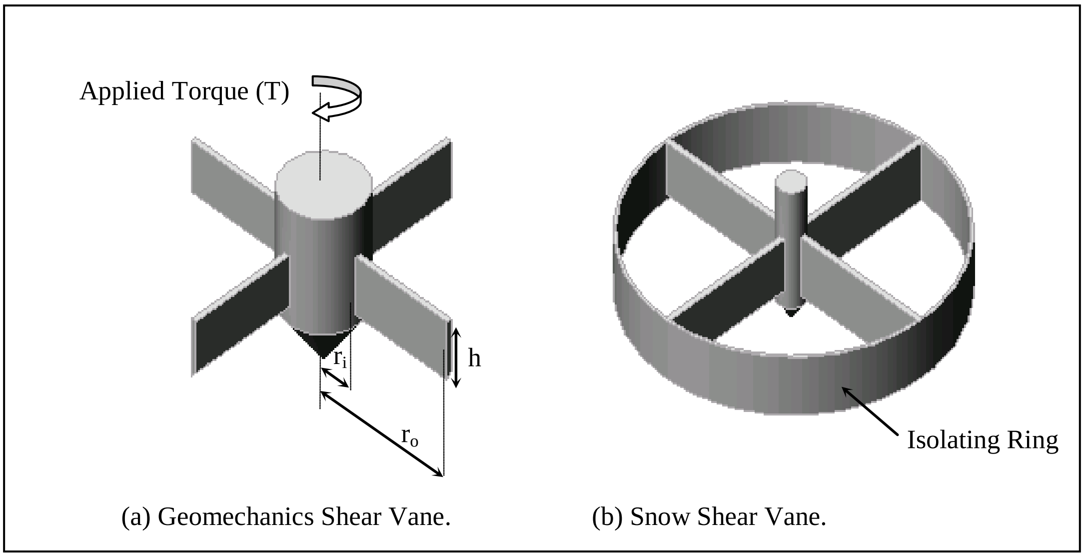


Figure 3.1: Mechanics of Shear Vane.

The nature of the shear frame test requires that all snow above a weak layer (other than about 40mm used in the testing) be removed before the test takes place. This ensures a simple, single shearing action on the lower surface. The shear vane on the other hand is pushed deep into the snowpack causing the formation of four wedge shaped columns as a result of the end vane shape. For a single shear failure to occur in this situation these columns must also rotate as the end vane (and contained snow sample) rotates in failure.

Where a single shear occurs theoretical analysis assumes that the resisting torque provided by frictional contact between snow and the surface of the cylinder is negligible. In reality there will be a small component of resisting torque present due to the freezing of snow onto the outside of the isolating ring, friction of rotating snow columns on surrounding snow and due to the imperfect cylindrical shape of the isolating ring. Analysis of this single shear situation is provided in *Equation (3.2).*

$$T_{\max} = \tau_{ShearVane}\left[\left(\pi r_o^2 - \pi r_i^2\right)\left(r_i + \frac{2}{3}(r_o - r_i)\right)\right] \tag{3.2}$$

When pushed deep into the snowpack shear failure occurs at both the lower and upper surfaces of the end vane resulting in a double shear failure. Analysis of this double shear situation is provided in *Equation (3.3).*

$$T_{\max} = \tau_{ShearVane}\left[2\left(\pi r_o^2 - \pi r_i^2\right)\left(r_i + \frac{2}{3}(r_o - r_i)\right)\right] \tag{3.3}$$

3.3 Potential Advantages of Prototype Device

Operating from the snow surface the shear vane offers many potential advantages over existing snow stability equipment. One of the major advantages being the rapid testing time allowing the assessment of numerous slopes of varying aspect and elevation within a relatively short period of time. As previously mentioned spatial variation in snow cover distribution and properties is extremely diverse and a significant cause in avalanche forecasting errors. By utilising a highly portable, lightweight device it is believed a better understanding of the avalanche risk to an entire area or mountain range can be obtained.

This ability to take a large amount of measurements relatively quickly may allow the location and investigation of “deficit zones” within a snow slope. This ability will allow the study of the parameters critical for avalanching and provide greater insight into the mechanism of avalanche release. Investigation of this theory would require considerable testing on highly unstable slopes or in the unreleased crown region of actual slab avalanches.

Present snow stability methods have few quantitative mechanical tests, limited largely to the shear frame and various force penetrometers. As the relationship between quantitative shear frame measurements and the shear strength of failed avalanche slabs is well documented, correlation of the rotational shear tester to the shear frame may allow the accurate determination of the shear strength of an entire snow slope. Being a quantitative measure also allows the potential to compare data between areas, regions or even different operators. This information exchange will have particular benefits in situations, such as that of Switzerland’s avalanche warning service, where the forecasters do not usually perform the vast majority of snow observations (Wiesinger and Schweizer, 2000).

A further benefit of this testing method comes as a result of all the overlying snow layers remaining in place during the course of the test. It is also well documented that the shear strength of a weak snow layer is dependent on loading acting in a direction normal to the shear plane, however many tests require this overburden to be removed and therefore fail to take it into account in strength calculations.

3.4 Initial Field Study

The overall aim of this Master’s research was to prove or disprove the ability of this concept to aid snow stability evaluation by comparison with currently recognised methods. As a tremendous amount of experience is required for accurate avalanche forecasting, (even seemingly simple tests like the shear frame test require considerable experience to reliably perform), the vast amount of early fieldwork (winter 1999) was based on intuitive feel and qualitative assessments.

This initial field study was carried out over a wide geographical area and highly variable snow and meteorological conditions with most testing centred around Canterbury’s Craigieburn and Torlesse Ranges. Where possible, assessments were carried out in conjunction with professional snow stability advice provided by the Broken River ski field snow safety patrol.

3.4.1 Objectives

The objectives of this initial field study were to;

- Gain experience in traditional snow stability evaluation methodology and equipment,
- Gain experience in using the shear vane,
- Assess ability of shear vane to measure shear strength within a snow layer,
- Assess ability of shear vane to measure shear strength at the interface between snow layers,
- Identify potential improvements to the shear vane.

3.4.2 Observations

Throughout this initial field study the shear vane showed considerable promise in locating weak snow layers. The following represent the main observations noted during this investigation.

1. When the end vane was located directly above a shallow sliding layer very little torque application was required, resulting in a single shear failure in the weak basal layer. As depth of the weak interface increased beyond approximately 300mm a complicated double shear was found. Lower surface failure was again in the weak basal layer however the upper surface failure was found to occur either at the upper surface of the end vane or at some point above it. Failure at this surface was not always in a readily observed plane but often occurred in a complex three-dimensional pattern. Measurement depths greater than about one meter generally resulted in simple double shear failure.
2. In thick (greater than 50mm) homogeneous snow layers, torque measurements increased with increasing hand hardness. Layers with a hand hardness measurement of fist or four-fingers could easily be located at any depth in the snowpack, up to the two meter limit of the extension rods.
3. The presence of ice layers caused considerable testing difficulties. A large vertical impact force was required to break through the thicker of these layers often to the detriment of the instrument. Even more importantly it was not possible to take measurements of thin, weak snow layers or weak interfaces directly below an ice layer or layer of very hard, consolidated snow. In the majority of cases these underlying layers were destroyed when the shear vane was inserted.
4. Torque values were found to be dependent on loading rate with greater torque application speeds resulting in lower measured torque values.
5. Measurement difficulties were encountered with moderate to very high strength snow layers as overloading of the torsion spring occurred without failure of the snow sample.
6. The main causes of unreliability and non-repeatability for the torque measurements were;
    - Dial slippage providing false torque readings.
    - Difficulty reading torque measurement as value is “lost” at failure.
    - Permanent deformation of torsion spring due to overloading.
    - Non-linear characteristics of torsion spring due to vertical spring bending.
    - Torque application unscrews extension rods and end vane.

3.5 Instrument Modifications

As a result of the deficiencies noted during this initial field study the following modifications, as shown in *Figure 3.2*, were carried out. These modifications included;

- Dial suitably keyed to shaft.
- Magnetic clutch system installed to maintain maximum torque reading after snow failure.
- Maximum/minimum stops added.
- Spring locating collars added to centrally locate spring.
- Counter-clockwise torsion spring fabricated so torque application does not unscrew connections.
- Nylon bushes were replaced with sealed deep groove ball bearings.

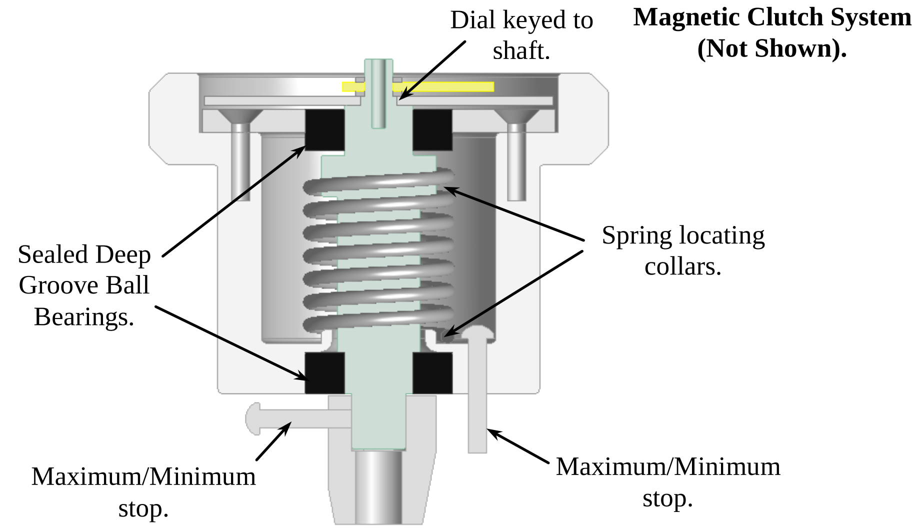


Figure 3.2: Modifications to Shear Vane Instrument Head.

In addition to these modifications a number of end vanes of differing dimensions and shape were designed and fabricated. The purpose of this being to measure snow over a wider range of strengths and to correlate with shear frames of standard cross-sectional area. These end vane dimensions are summarised in *Table 3.1* and illustrated in *Figure 3.3.*

Table 3.1: End Vane Dimensions.

End Vane	Cross-sectional Area (cm^2)	Vane Height (mm)	Isolating Ring
1	250	25	Present
2	250	25	Absent
3	100	25	Present
4	100	25	Absent
5	50	25	Present
6	50	25	Absent
7	50	10	Absent
8	50	5	Absent
9	10	2	Absent

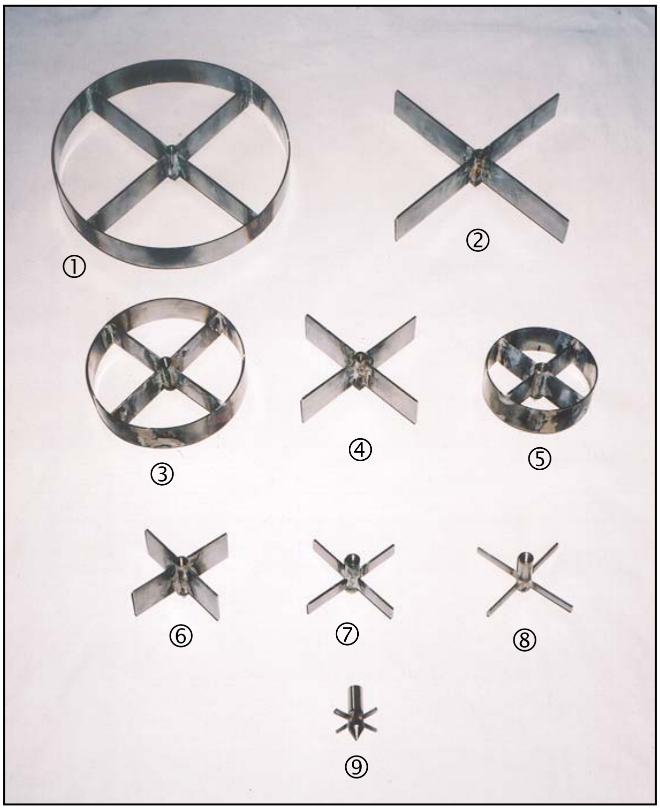


Figure 3.3: End Vane Configurations.

3.6 Discussion

The shear vane presented during this chapter exhibits considerable ability in locating weak layers and weak layer interfaces within the seasonal snowpack. Particularly promising is the ability to locate thick weak layers at any depth and the ability to locate shallow weak interfaces.

Numerous difficulties were also encountered during this initial investigation with the main contributors being;

- The complex failure pattern of deep failure layers,
- Difficulty in obtaining measurements below ice or hardened snow layers,
- Deficiencies with the instrument.

The modifications presented in the previous section have addressed issues regarding the functioning of the instrument. The ability to obtain measurements below hardened snow layers and the difficulties associated with the complex failure pattern of deep snow layers however have yet to be solved.

The use of this instrument as a quantitative measure of snow stability is still unknown as are the effects of vane size, presence of the isolating ring and the depth of the failure layer. Investigation of these parameters is presented in the following chapter along with correlation of shear strength measurements with values obtained from the shear frame.

Chapter 4

Field Investigation

This chapter provides a summary of the fieldwork carried out during the winter of 2000. The aim of this investigation being to determine the shear vane design parameters critical for evaluating snow slope stability.

4.1 Study Area

4.1.1 Location

All fieldwork presented in this chapter was carried out in the Craigieburn Range in the immediate vicinity of Broken River Ski Field, as shown in *Figure 4.1*.

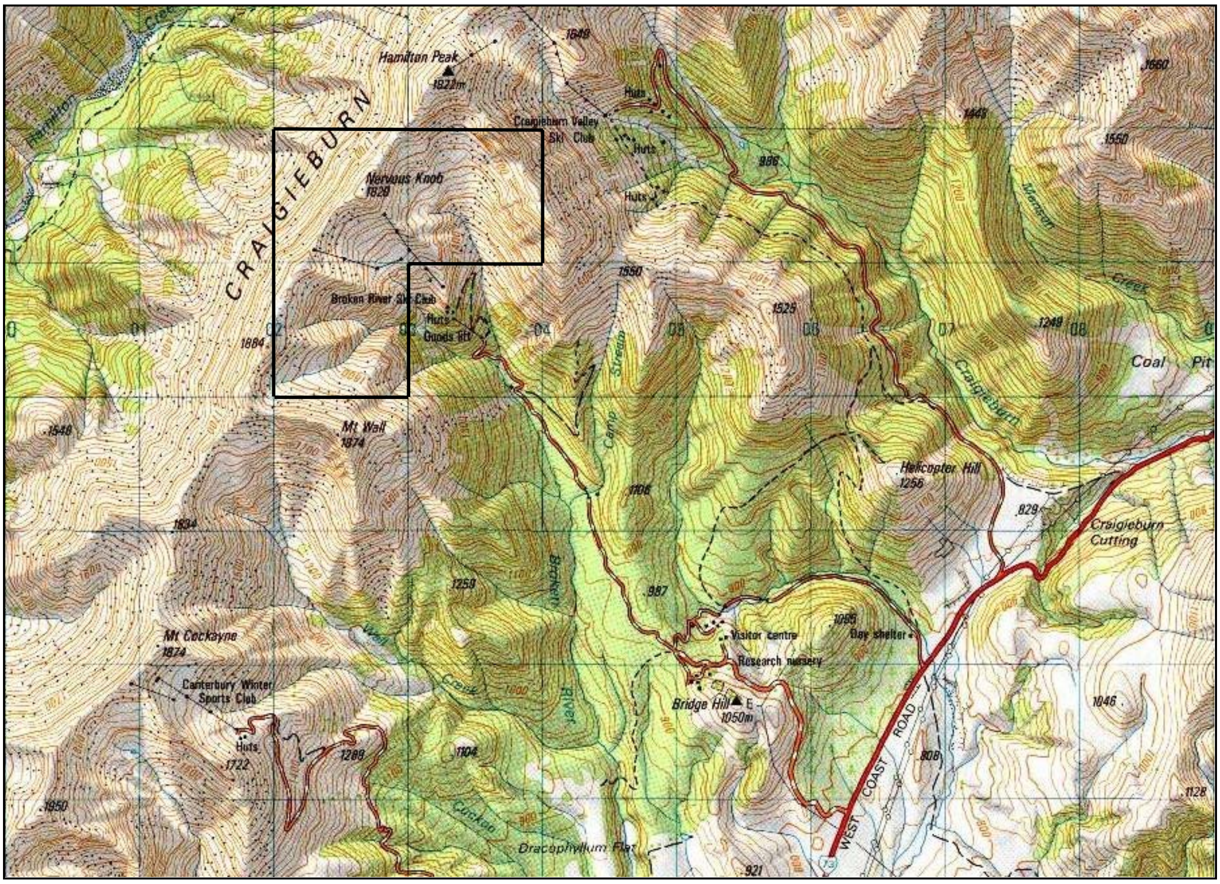


Figure 4.1: Topographical Map of Study Area Location.

The Craigieburn Range forms part of the Southern Alps of New Zealand, running in a northeast – southwest direction for a distance of 26km, approximately 20km east of the main divide. Situated approximately 120km west of Christchurch on State Highway 73 (the Arthur's Pass Road), this study area provided relatively easy access to alpine terrain enabling an observer to be in the upper avalanche start zones within two hours of leaving Christchurch. This close proximity, combined with the accommodation lodges being situated at high altitude enabled many observations to be carried out over a wide range of snowpack and meteorological conditions and was a significant contributor to the volume of experimentation carried out during this research.

The terrain of this area, typical of the northern Craigieburn Range, is characterised by glaciated cirque basins modified by fluvial and mass movement erosion processes (McGregor, 1989). These geographic processes have resulted in the formation of large bowl shaped avalanche start zones, which descend steeply into narrow gullies with runout zones well below bush line in altitude. This topography provides very few regions of level ground and the few regions that do exist tend to be occupied by ski area facilities or have heavily modified snow conditions due to the action of skiers, snowboarders and ski field machinery. As a result all testing was carried out on steep slopes of varying inclination between 30º and 48º, often beyond the ski area boundary.

4.1.2 Climate

The snow climate of the Craigieburn Range is most typical of intermontane or coastal-transition regions which experience characteristics typical of both maritime and continental snow climates. Winter conditions are cold enough for the development of depth hoar to occur while also experiencing maritime characteristics sufficient to allow rain to fall to high elevation at any time during the winter (Prowse, 1981).

The Craigieburn Range is considered 'warm' in comparison to other alpine areas however the winter months of June, July, August and September tend to be dominated by below freezing temperatures, above average precipitation and general windiness above 1500m (McGregor, 1984).

4.1.3 Meteorological Conditions of Winter 2000

In general, winter 2000 was very warm with the national mean temperature 0.9°C above average and the second highest recorded for winter since records began in the 1850's. Precipitation was above average in many South Island alpine regions, including the Craigieburn Range, which recorded 122 percent (486mm) of its average winter rainfall at the Craigieburn Forest observation site (New Zealand Mountain Safety Council, 2001).

June weather was typically unsettled with several severe southerly storms (2nd and 11th-13th June) bringing extensive snowfall to mountainous regions. This early snowfall was followed by a lengthy period of very settled weather which lasted up until the last few days of July. During this period snowfall in the Southern Alps was infrequent and several of the smaller ski areas, devoid of snowmaking facilities, were forced to close temporarily. August brought above average precipitation in the Craigieburn Range with a procession of anticyclones and troughs of low pressure over the South Island. This resulted in heavy to very heavy snowfall at Broken River ski field on the 12th, 18th and 26th of August.

4.2 Objectives

The main objectives of this field investigation were to;

1. Correlate shear strength measurements of the shear vane to those obtained by the standard shear frame test.
2. Investigate the effects of vane diameter, vane height and vane isolating ring on shear strength measurements with the aim of determining the critical parameters in assessing snow slope stability.
3. Investigate the effect of snow normal loading on shear strength measurements.
4. Investigate methods of measuring the average snowpack density above a weak layer or weak layer interface.

4.3 Equipment

In addition to standard snow profile observation equipment and the necessary alpine safety equipment the following apparatus was used during the course of this study.

- Shear vane,
- Standard shear frame ($100cm^2$ and $250cm^2$) (See *Figure 2.5*),
- Depth shear frame ($100cm^2$ and $250cm^2$) (See *Figure 4.2*),
- Split core sampler (See *Figure 4.4*),
- HydroSense and Aquaflex soil moisture measuring systems,

4.3.1 Depth Shear Frame

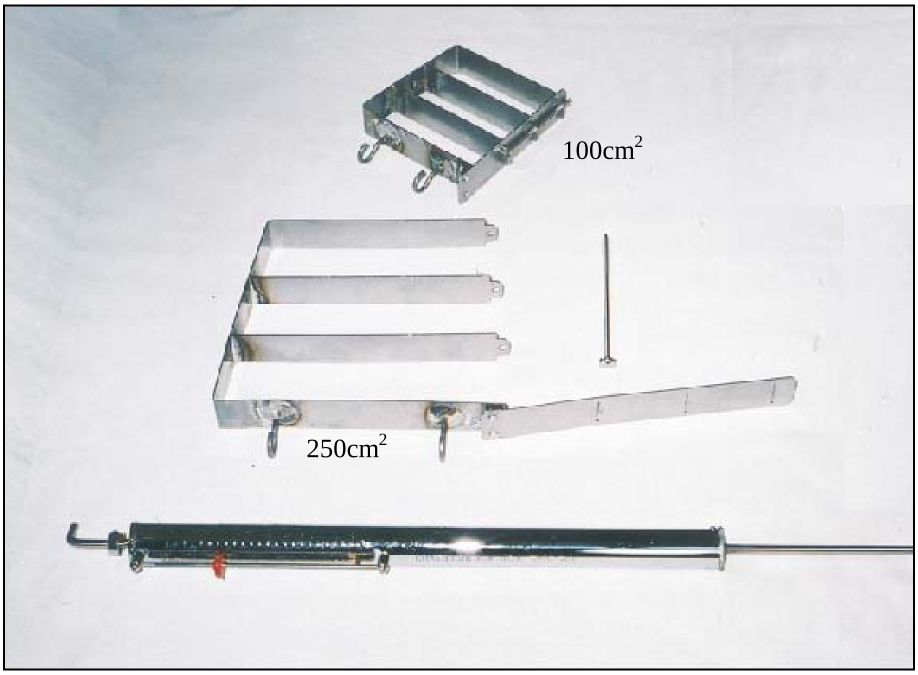


Figure 4.2: Depth Shear Frames. $100cm^2$ and $250cm^2$.

Specifically developed during this research the depth shear frame, illustrated in *Figure 4.2*, allows traditional shear frame measurements without removing overlying snow layers. With the hinged member open the frame is inserted into an isolated snow column just above a weak layer or weak layer interface at a direction parallel to the slope angle. The hinged member is then closed and a pin inserted to lock it in place. Force application is in a similar manner to the standard shear frame.

Two frames of this design were fabricated, again with a height of 25mm and cross-sectional area of 100cm^2 and 250cm^2. Detailed drawings of these instruments, along with the 250cm^2 standard shear frame are provided in *Appendix C.*

4.3.2 Split Core Sampler

A core sampler was designed and fabricated with the main purpose of determining the average snow density, and therefore weight of snow, above a snowpack weakness. The main design features of this instrument included;

- Lightweight, portable instrument with a total weight of 0.45 Kg,
- Two 1.5m lengths allow samples to be extracted from snow up to 3m deep,
- A *Spring Core Catcher* retains cohesionless snow in the sampler on removal from snowpack,
- Rugged construction enables instrument to be pushed through very hard snow layers,
- Split core design enabled visual inspection of undisturbed snow samples,
- Fabricated from standard sized PVC piping this instrument is easily fabricated and low cost,
- Design attempted to minimise sample disturbance by obtaining the lowest possible *Area Ratio* where;

$$Area\,Ratio \;=\; \frac{D_e^{\,2} - D^2}{D^2} \tag{4.1}$$

D_e = External Cutter Diameter,
D = Internal Cutter Diameter,

- Design incorporated an *Inside Clearance Ratio* to reduce the friction while inserting the sampler into the snowpack. This ratio was however minimised to reduce lateral expansion of the snow sample.

$$Inside\,Clearance\,Ratio \;=\; \frac{D_i - D}{D} \tag{4.2}$$

D_i = Internal Sampler Diameter.

Area ratios of less than 15% and inside clearance ratios of between 0.5% and 1.5% have been proposed for undisturbed soil samples (Lancellotta, 1993).

4.3.3 HydroSense and Aquaflex Soil Moisture Measuring Systems

Time Domain Reflectometry (TDR) is a relatively new method for measuring water content properties, being introduced to soil applications in the early 1980's (Topp et al., 1980) and first used on snow in the early 1990's (Schneebeli and Davis, 1992). TDR is an electrical measurement technique where velocity, impedance and attenuation of an electromagnetic pulse are modified by the properties of the material surrounding the TDR cable. A change in cable impedance also results in a portion of the electromagnetic pulse being reflected at the location of this impedance change. Therefore by monitoring the pulse reflection signal it is possible to locate a change in material properties and, with analysis, determine what those properties are.

The HydroSense and Aquaflex soil moisture measuring systems incorporate highly developed electronic systems in conjunction with TDR technology to determine soil moisture content. The Aquaflex system measures average soil moisture content over the 3 meter length of a coaxial cable, with values being calibrated depending on soil type. Temperature changes are also compensated for in the software provided. The HydroSense system consists of a compact handheld display with two 12 or 20 cm measurement probes inserted into the soil surface. Measurements are again averaged over the length of the probe and are displayed on a liquid crystal display screen as a water content percentage.

TDR as a measure of snow wetness and density is, at present, in its infancy with recent publications indicating a direct relationship between snow liquid water content and dielectric coefficient (Camp and La Brecque, 1992). A similar relationship is reported to exist between density and dielectric coefficient (Huebner et al., 1997).

This opens up several areas of interest which will be addressed during this investigation, including;

1. The possibility of measuring changing ‘in situ’ water content characteristics with onset of meteorological events.
2. The possibility of determining the density of thin layers within the snowpack.

The first possibility of measuring changing water content characteristics would provide particular benefits to strongly maritime snow climates, such as that experienced on the Milford Sound highway, where water retention and filtration effects strongly influence avalanche activity (Carran et al., 2000).

4.4 Experimental Procedure

The following comparative shear tests were carried out throughout August and September 2000 upon establishment of the seasonal snowpack within the study area. In total over 20 potential failure layers were investigated during this field study with comprehensive testing being completed on 16 of those layers. In those situations where testing was abandoned this was a result of;

- Significant changes in meteorological conditions during experimentation. This predominantly included temperature changes greater than 10°C and the onset of rain,
- Identification of suspect snowpack stability,
- Mechanical failure of test equipment,
- Location of discontinuities within the snowpack.

4.4.1 Test Location Selection.

Prior to the onset of winter 10 observation areas were established, each consisting of an area 3m x 6m. Unfortunately very heavy early season snowfall resulted in the complete burial of many of these sites (and a high altitude weather station) and the ensuing action of skiers and snowboarders resulted in 8 of these areas being abandoned. Specific test locations were therefore selected on the day of experimentation with consideration given to the following factors.

- Snow stability and general alpine safety considerations,
- Requirement for testing to be carried out on unmodified snow conditions away from the influence of skiers, snowboarders and ski field machinery,
- Requirement for testing to be carried out on uniform snow slopes,
- Requirement for testing to be carried out a significant distance from terrain influences.

4.4.2 Snow Profile Analysis.

Upon selection of a suitable study location traditional snow profile analysis was carried out. This required digging a snow pit to the ground surface and observation of;

- Geographic information of test location (site description, elevation, aspect, slope inclination),
- Meteorological conditions (sky cover, precipitation, wind, air temperature),
- Snowpack temperature profile,
- Location (depth and thickness) of significant snow layers,
- Hardness, grain form, grain size, free water content and density of significant layers.

4.4.3 Shovel Shear Test.

The shovel shear test was then performed to locate all weak layers or weak layer interfaces within the snowpack. One of these layers was then selected for use in all of the following comparative shear tests with selection being based on the weakness deemed to be the most significant influence on snow slope stability. As the following procedure typically took between 4-6 hours only one layer was investigated on a single day, often with a snow pit being re-excavated on following days to investigate further weaknesses.

4.4.4 Average Snow Density Measurement.

Using a snow density tube and spring balance the average snow density above the selected layer was calculated. The density tube was inserted from the snow surface in a direction perpendicular to snowpack layering with a total of five measurements being taken for each test location. Average snowpack density was calculated according to *Equation 4.3*, where $Mass_{Total}$ refers to the combined mass of the density tube and the contained snow sample, while $Mass_{Density\ Tube}$ refers to the mass of the density tube alone.

$$Average\ Snowpack\ Density\ (\rho)\ =\ \frac{Mass_{Total} - Mass_{Density\,Tube}}{Cross\ Sectional\ Area \times Depth\,of\ Failure\ Layer} \qquad (4.3)$$

4.4.5 Surface Shear Strength Measurements.

The snow pit was then extended for a length of about 6m and to a depth approximately 200mm below the layer of interest. Using a snow saw a bench was constructed running parallel and approximately 40mm above the selected layer. This bench was approximately 400mm deep and ran the entire length of the snow pit. Using this pre-fabricated snow bench surface shear strength measurements were performed using the 100cm^2 and 250cm^2 shear frames and the shear vane with end vanes of comparative area (end vane no's. 1 and 3). Tests were carried out directly behind and progressively upslope of the preceding measurement, as shown in *Figure 4.3,* with a series of 15 tests being performed for each instrument across the slope. Maximum force and torque readings were recorded for each respective instrument.

For the remainder of this thesis these tests are referred to as surface shear frame and surface shear vane tests respectively. Analysis is performed using *Equation (2.1)* for the shear frame and *Equation (3.2)* for the single shear failure of the shear vane.

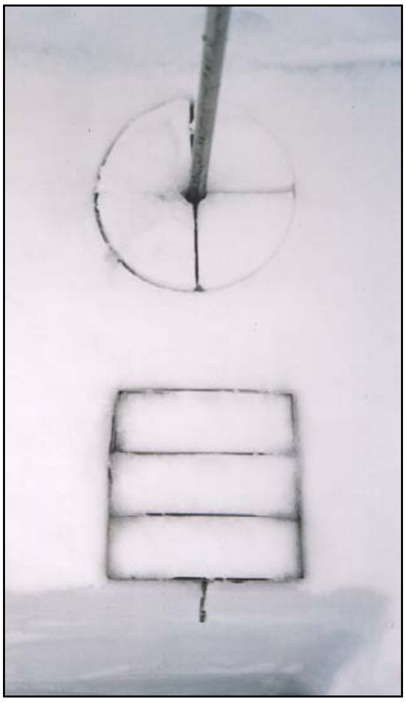


Figure 4.3: Surface Shear Strength Measurements.

4.4.6 Depth Shear Vane Measurements.

Directly behind and again progressively upslope end vane no's 1-9 were tested in the unbenched snow. These vanes were inserted into the snowpack perpendicular to snowpack layering and to a depth so that the end vane was either in the snow layer being tested or the bottom of the end vane coincided with the weak interface. Maximum torque readings and the type of shear failure (if it was observed) were recorded.

This procedure was then repeated across the slope to give a total of 15 data values for each end vane. Shear strength was calculated using *Equations (3.1)-(3.3)* depending on the vane type used (ie. whether an isolating ring was present) and the type of failure observed. For the remainder of this thesis these tests are referred to as depth shear vane tests.

4.4.7 Depth Shear Frame Measurements.

Tests using both the 100cm^2 and 250cm^2 hinged shear frames (*Figure 4.2*) were performed after every three sets of the depth shear vane tests described above. This involved isolating a vertical snow column in the unbenched region of the snow pit of similar cross-sectional area to the frame being tested. The frame was then inserted directly above the identified weak layer and the force required to cause failure of the isolated snow column was recorded. Analysis is similar to that of the surface shear frame, however the down-slope component of the snow column weight needs to be taken into account. Therefore shear strength was calculated according to *Equation (4.4)* below.

$$\tau_{Depth\,Shear\,Frame} = \frac{F - g(\rho_{Average\,Snowpack} \times Volume_{Snow\,Column} + Mass_{Shear\,Frame})\sin\theta}{Area_{Shear\,Frame}} \qquad (4.4)$$

4.4.8 Split Core Sampler

At each of the 16 locations used in the comparative shear tests described above the split core sampler was used to extract 5 samples to the depth of the selected layer. By splitting the sampler open, as shown in *Figure 4.4*, the snowpack structure could be investigated. The location (depth and thickness) of significant snow layers was recorded as well as the snow crystal type and grain size. Average snow density above the selected layer was also measured with this device.

Figure 4.4: Split Core Sampler.

4.4.9 HydroSense and Aquaflex Soil Moisture Measuring Systems

These tests carried out for the HydroSense and Aquaflex soil moisture systems were of an introductory nature and were essentially an initial indicator as to whether these specific devices could be used or developed to measure snow moisture content and/or snow density.

The HydroSense soil moisture system was calibrated using an approximate measure of snow liquid water content where a known mass of water is sprayed onto a known mass of dry snow. This procedure involved the collection of large homogeneous snow samples with readings using the HydroSense instrument taken after each stepwise addition of sprayed water. Samples were contained in a large bucket with numerous holes over the bottom so excess water could drain away. This excess water was collected and weighed after each spraying. Three different snow types were tested in this manner and consisted of;

- Rounded snow grains,
- Faceted snow grains,
- Partially decomposed snow crystals.

Calibration of the Aquaflex soil moisture system was carried out with a similar method however the 3 meter length of the coaxial cable was buried within a large sheet metal trough. Again water was sprayed onto the snow surface in a stepwise fashion and the drained water was collected and weighed. The readout from the Aquaflex system was recorded after each spraying.

4.5 Discussion of Results

The following section describes the results obtained from the comprehensive analysis of 16 observed snowpack weaknesses. These weaknesses consisted mainly of layers of partially decomposed snow crystals or of weak interfaces resulting from poor bonding of new snow to the melt-freeze crust formed by July's extended period of settled weather. Snow stability was generally in the range of 'Good' to 'Fair' during the period of experimentation with few very weak layers observed. In all over two thousand shear tests were carried out during this research.

4.5.1 Shear Frame Tests

Traditional shear frame tests, performed with frames of $100cm^2$ and $250cm^2$ cross sectional area were used throughout this study as the standard reference for the newly developed instrumentation. A summary of shear strength measurements obtained from these two devices is illustrated in *Figure 4.5*. Although considerable scatter is observed, particularly for high strength snow layers, it is clearly evident a linear relationship exists between these shear frames, with the smaller $100cm^2$ frame indicating higher shear strength.

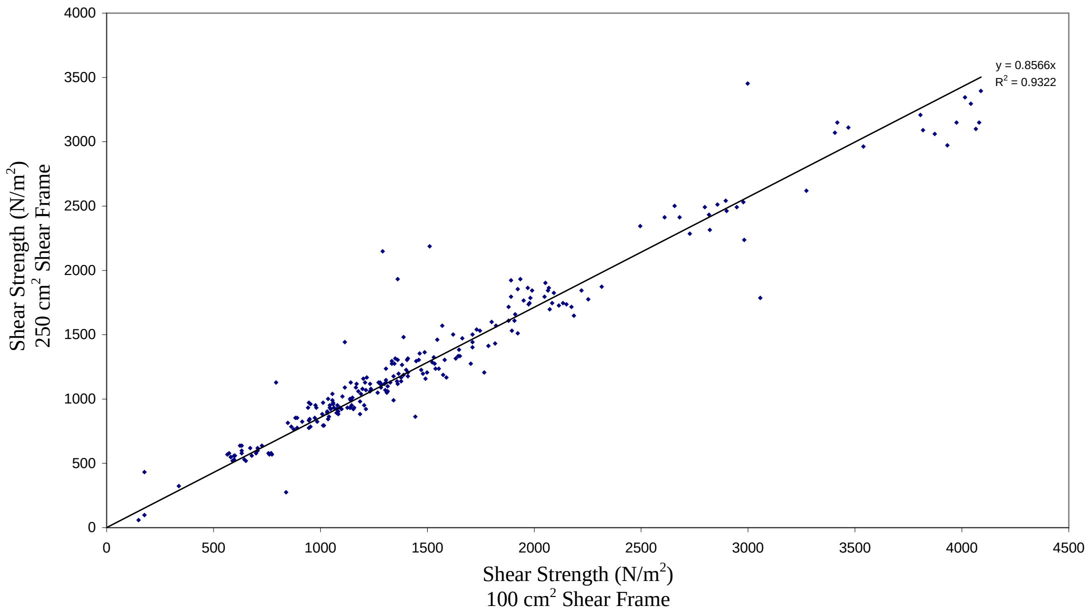


Figure 4.5: Comparison of 250 cm^2 and 100 cm^2 Shear Frames.

This higher measured shear strength obtained with the $100cm^2$ shear frame is evident in previous work which has focussed on the development of the shear frame size correction factor to take into account such size effects as well as differences between measured shear strength and the actual shear strength of an entire snow slope (Sommerfeld et al., 1976; Fohn, 1987). Application of a *least squares fit* to the experiments of Fohn establishes the size correction factor *C*, according to *Equation (4.5)* below where *A* is the shear frame cross sectional area (m^2) and the size correction factor *C*, represents the ratio of the measured shear strength to the true shear strength of a snow slope.

$$C = 15.95A^3 - 13.25A^2 + 4.029A + 0.526 \tag{4.5}$$

Theoretical results using this relationship indicate an expected shear strength ratio of 0.9128 which compares well with the ratio of 0.8566 found from the presented experimental results. Differences between these values are most probably a result of;

- High variability in snow properties experienced in the intermontane snow climate of the study area,
- Reduced alignment difficulties of the large shear frame due to a significant proportion of tests being carried out in thick homogeneous snow layers,
- Operator variance.

Also highlighted in *Equation (4.5)* is the experimentally observed phenomenon that the mean measured shear strength is considerably higher than the mean measured stress for snow layers known to have failed (Roch, 1966; Sommerfeld and King, 1979). In correlating any new instrumentation to these shear frames it must be remembered that these devices, without correction, do not provide a true indicator of slope stability and in fact overestimate it (by 78% in the case of the 100cm^2 shear frame).

4.5.2 Comparative Shear Tests

Early testing with the shear vane indicated low strength snow was required (especially for the large vane sizes) otherwise the instrument would reach its maximum stop before failure of the snow sample occurred. The option of replacing the torsion spring with a spring of greater stiffness was considered, however the low strength layers were handled adequately with this system and it is these layers that are of prime concern for this study. As many of the layers tested involved snow of moderate strength the 250cm^2 shear vanes (end vane no.'s 1 and 2) returned a greater number of maximum readings than actual data values and hence their results were excluded from this discussion. Values for the remaining end vanes are presented as an average value of all the tests performed on a single snowpack layer or interface. Due to the wide scatter of results error bars are not plotted.

Figure 4.6 shows a linear relationship exists between the 100cm^2 shear frame and the 100cm^2 (ϕ113mm, h=25mm, ring) shear vane for both surface and depth measurements. Surface shear vane measurements indicated a lower shear strength than the shear frame with a trend line gradient of 1.2602.

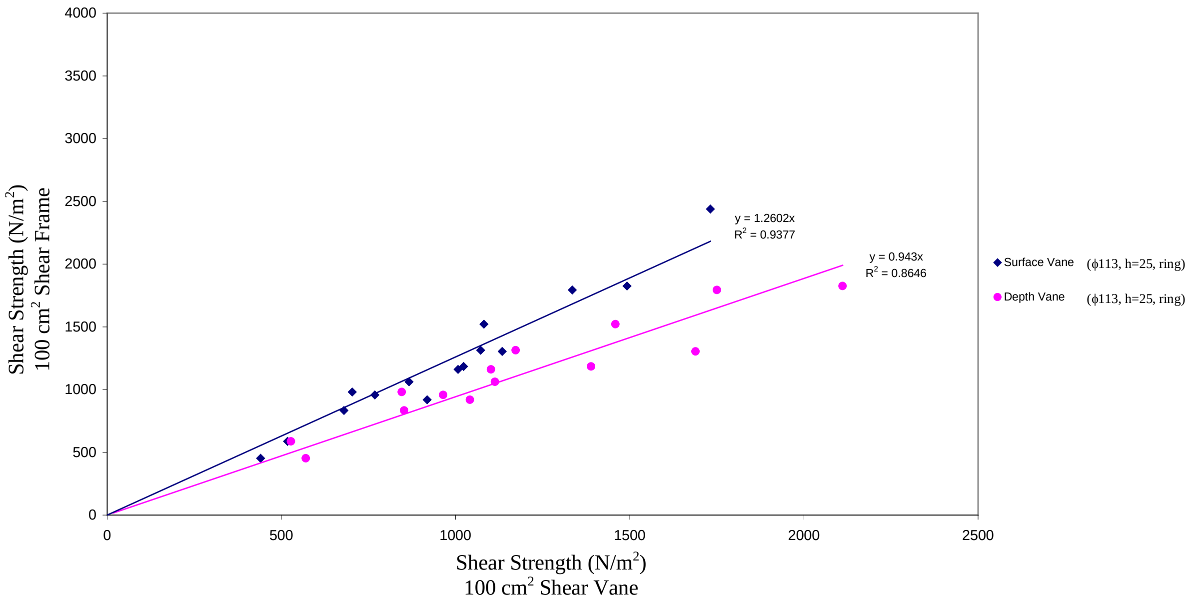


Figure 4.6: Comparison of 100cm^2 Shear Frame and 100cm^2 Shear Vanes.

All depth vane measurements produced greater shear strength values than similar surface tests on the same layer. This would be expected when testing a weak interface as the shear failure occurring on the upper surface of the end vane (when the vane is tested at depth) is likely to be in a stronger snow layer (assuming the basal layer is the weakest of all snowpack layers), therefore resulting in a greater average shear strength. When measuring in thick homogeneous snow layers however, it would be expected the upper surface shear strength would be similar to that of the lower surface resulting in similar shear strength values for both the surface and depth measurements. This was not the case and leads to the question of whether the weight of overburden snow is influencing shear strength measurements. Investigation of measured shear strength values obtained with the depth shear vane and the stress imposed by the snow overburden revealed no discernable relation.

4.5.3 Effect of Vane Cross Sectional Area

The shear tests reported in this and the following two sections refer to the analysis of shear vane tests carried out in the unbenched region of the snow pit (ie. depth shear vane measurements). Analysis has been carried out in this way, as this is the mode in which this instrument is intended to be used and therefore, even though there may be a combination of factors acting, it is expected to provide a better reflection of actual performance characteristics.

Comparison of the 100cm^2 (ϕ113mm, h=25mm, ring) and 50cm^2 (ϕ80mm, h=25mm, ring) shear vanes indicates a higher strength from the larger shear vane than the smaller vane, as is shown in *Figure 4.7*. One possibility is that this is the result of an increased probability of the larger vane encountering strong discontinuities within the snowpack. This theory is unproven and appears to be contradictory to shear frame size effects where smaller frames experience greater strength measurements. A more likely scenario is that the small area of the 50cm^2 vane makes a high percentage of snow disturbance when the vane is inserted resulting in disproportionately low shear strength values.

Unfortunately the inability to obtain sufficient useful data from the 250cm^2 shear vane (ϕ179mm, h=25mm, ring) limited the analysis that could be performed in relation to vane cross sectional area effects.

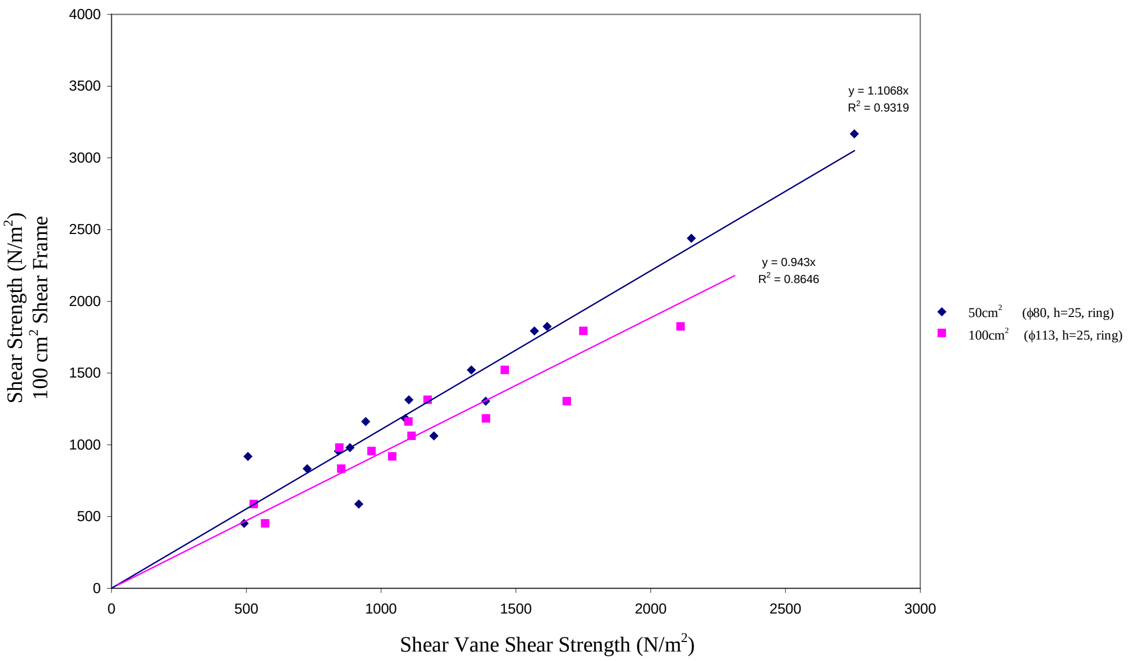


Figure 4.7: Effect of Shear Vane Cross Sectional Area.

4.5.4 Effect of Vane Height

Shear strength measurements obtained from vanes with a vertical height of 25mm, 10mm and 5mm ((ϕ80mm, no ring) end vane no.s 6, 7, and 8) indicate excellent agreement, as is shown in *Figure 4.8*. Generally weak layers were sufficiently large to allow the entire vane height to be contained within the tested layer resulting in comparable results between the different vanes. When testing interfaces it was very difficult to align the vanes exactly with the layer being tested which was often over a meter deep in the unbenched snow. This no doubt resulted in the shearing of the snow either side (above and below) the interface, even with the small 5mm vane, again leading to similar results for all three pieces of equipment.

The use of a miniature vane with a height of 2mm and cross sectional area of 10cm^2 ((ϕ37mm, h=25mm, ring) end vane no. 9) provided very low shear strength values in this situation but its small size meant it was prone to breakage when inserted into the snowpack. As a result of these failures this vane was not used extensively.

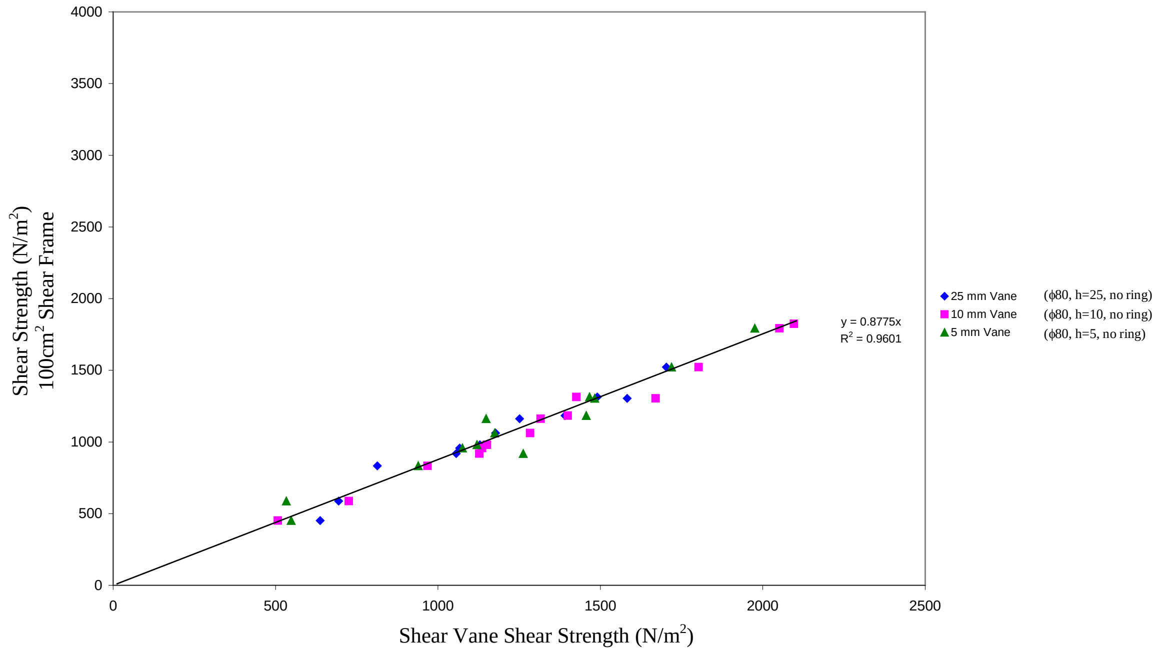


Figure 4.8: Effect of Shear Vane Height.

4.5.5 Effect of Vane Isolating Ring

The isolating ring essentially isolates the vane from the effects of side shear limiting the failure surface to the upper and lower surfaces of the end vane. Removal of the isolating ring therefore resulted in a significant increase in measured shear strength, as is shown in *Figure 4.9*. This increase also resulted in the inability to take measurements with the 100cm^2 x 25mm vane with no isolating ring (end vane no. 4).

When testing layer interfaces the vane with the isolating ring was much easier to locate, as a dramatic decrease in the torque required to cause failure of the snow column was observed. The vane with no isolating ring, on the other hand, wasn't as responsive to changes in basal shear strength and for this reason it is the belief of the author that a vane isolating ring is essential for this concept to be a success.

Inclusion of a vane isolating ring also had the added advantage of increasing the vane rigidity and strength. This would allow the fabrication of smaller end vanes for testing thin layers while being sufficiently strong to be pushed through hard ice layers without breaking.

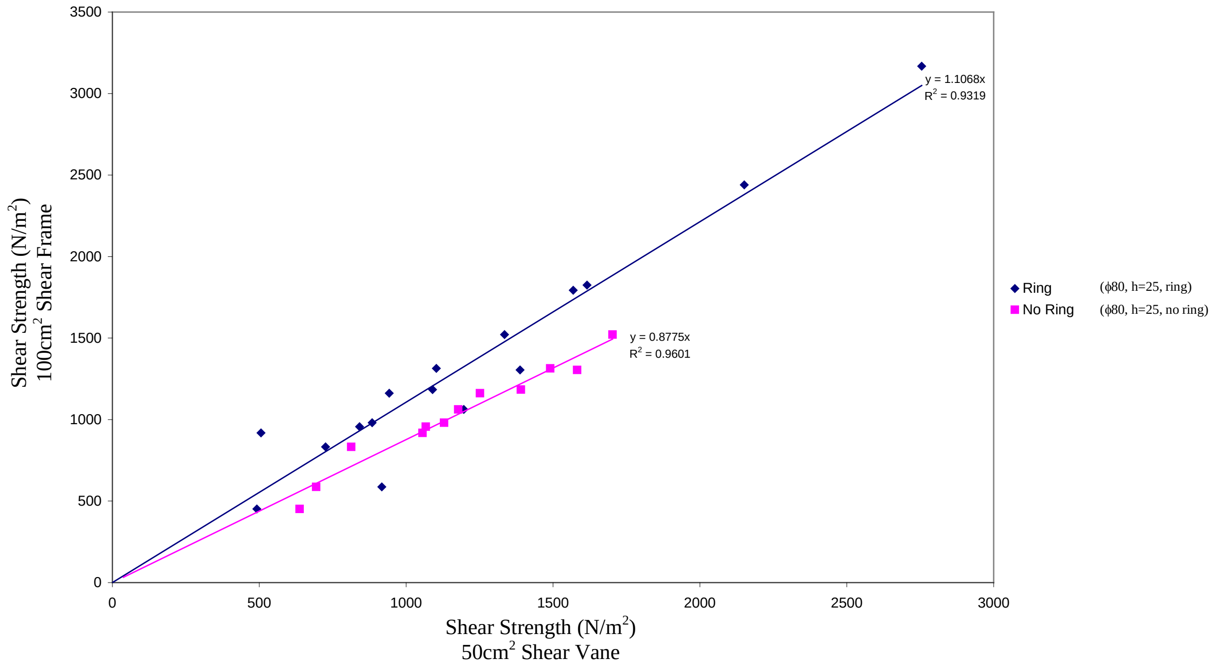


Figure 4.9: Effect of Shear Vane Isolating Ring.

4.5.6 Effect of Normal Loading on Shear Frame Measurements

Use of the newly developed depth shear frame (*Figure 4.2*), designed to enable the testing of weak layers with the overburden snow still in place, proved to be a difficult task. Firstly constructing an isolated snow column of the same cross sectional area as the shear frame require considerable practice and was best achieved by placing the shear frame on the snow surface and cutting around it with a snow saw. Further difficulties arose when inserting the frame into the snow column above the layer to be tested. Alignment with the weak layer was difficult to achieve and a large amount of disturbance was caused when the frame was inserted. For these reasons it was not possible to test the 100cm^2 depth shear frame with attempted tests resulting in the column collapsing completely or the disturbance being so great that the test could not be performed with any confidence.

The 250cm^2 depth shear frame was much easier to insert and allowed results to be obtained with reasonable repeatability. Testing with this device indicated a much greater shear strength than the traditional surface operated shear frame with an average shear strength value 2.288 times greater. Investigation of measured shear strength values and the stress imposed by the snow overburden revealed no discernable relation. This was a similar phenomenon as that observed with the shear vane. It is highly probable that this is a second order effect with the shear strength being related much more closely with the bonding characteristics of the weak layer or interface rather than the overburden influence. Never the less these results would suggest that the weight of snow overburden does have a dramatic effect on shear strength results and therefore the use of the traditional shear frame test as an indicator of slope stability has to come under question.

4.5.7 Split Core Sampler

The split core sampler provided a rapid means of obtaining snow samples with analysis of the contained snow layers providing comparable snow stratigraphy information to snow profile data. The identification of snowpack weaknesses however could not be carried out with this device as even relatively cohesive layers were broken apart either, while the sample was being collected or, when the sampler was opened up for examination. This resulted in multiple fracture lines, many of which did not relate to observed weaknesses.

The average snowpack density measured with this device was found to be comparable with the density tube measurements. This was provided the depth to which the sampler was inserted was recorded and used for density calculations as opposed to the length of snow in the sampler. Direct measurement of the depth from the sample itself proved to be erroneous and gave, on average, 12% greater snowpack density values than those obtained with the snow density tube. Again this is likely a cause of sample disturbance and compression during collection.

4.5.8 HydroSense and Aquaflex Soil Moisture Measuring System

The HydroSense soil moisture measuring system returned values of water content given as a numerical value between 0.80 and 0.99. As illustrated in *Figure 4.10* measured data values varied considerably between the three snow types tested. The low density layer of partially decomposed snow crystals returned usable results over a range between 1 and 8 percent liquid water content. Outside of this range returned values were stable on either 0.80 or 0.99 depending on whether liquid water content was above or below this range. Faceted snow grains returned usable values over the range 10 to 28 percent liquid water content, while rounded snow grains returned data values over the widest range, from 0 to 38 percent liquid water content.

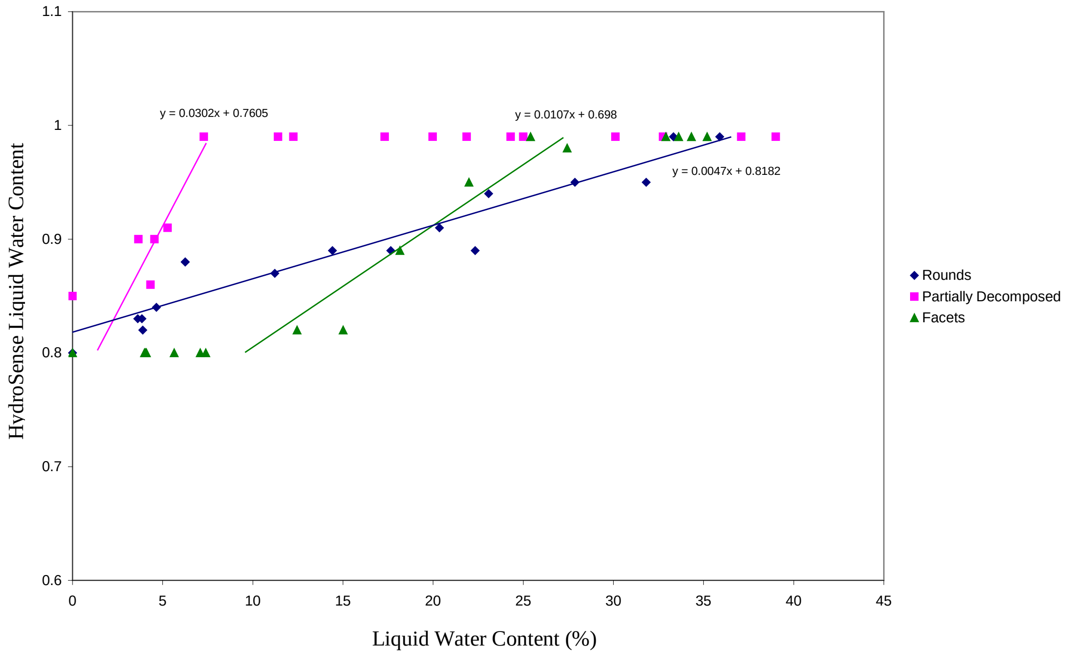


Figure 4.10: HydroSense Soil Moisture Measuring System.

Due to the wide variation in results observed with this instrument it is clear that calibration is required for each snow type, again placing reliance on the operator to obtain useful data. For these reasons this device was abandoned as a measure of liquid water content.

The Aquaflex soil moisture system produced a zero readout throughout testing even when completely submerged in a bucket containing a snow/water mixture. Equipment checks both prior to and following these tests (by immersing the coaxial cable in a bucket of warm water) indicated liquid water content close to 100%. These results suggest the cold temperatures of the test environment are affecting either the signal characteristics within the coaxial cable or the system electronics. Either way this system has not been able to measure snow moisture content.

The poor results obtained from these instruments are not all together surprising. Both instruments incorporate highly developed systems based on years of soils research and have not been developed or modified for use on snow. This development is beyond the scope of this research.

4.6 Summary

A comparison of the mean shear strength obtained for each instrument in shown in *Table 4.1*. For comparison an expected shear strength is provided for each instrument in relation to a 1000 N/m^2 shear strength value obtained with the 100cm^2 standard shear frame. Instruments are listed in order of magnitude. Based on *Equation 4.5* the estimated actual shear strength of an entire snow slope is also shown in this table.

Table 4.1: Summary of Shear Strength Measurements.

Instrument	**Expected Measured Shear Strength (N/m^2)**
50cm^2 x 25mm vane (No ring)	1140
50cm^2 x 10mm vane (No ring)	1140
50cm^2 x 5mm vane (No ring)	1140
100cm^2 vane	1060
100cm^2 standard shear frame	**1000**
50cm^2 vane	904
250cm^2 standard shear frame	857
100cm^2 vane (surface)	794
Estimated Actual Shear Strength	**565**

The significant results obtained during this field investigation included;

- All shear vanes exhibited a linear shear strength relationship with the shear frame, the standard reference used throughout this study.
- All shear measurements obtained (shear frames and shear vanes) indicated a greater measured shear strength than the expected actual shear strength of an entire snow slope.
- Surface shear vanes indicated lower shear strength than shear frames of similar cross sectional area and height.
- Measurements for both shear vanes and shear frames indicated greater shear strength when the snow overburden is present. No relationship was observed between shear strength and overburden stress in either instance.

- 50cm^2 shear vanes with vane heights varying between 5 and 25mm indicated similar shear strength measurements. It is possible that due to misalignment even the 5mm vane was not able to measure solely within the thin weak layer. A 10cm^2 vane with a vane height of 2mm indicated lower shear strength values but was prone to failure and was not used extensively.
- The effect of the vane cross sectional area is not conclusive due to the inability to obtain results from the 250cm^2 shear vanes. Results indicate a greater measured shear strength from the 100cm^2 shear vane than those obtained from the 50cm^2 shear vane. This effect is possibly due to the increased proportion of snow disturbance when using the smaller vane.
- Inclusion of a vane isolating ring reduced the measured shear strength by isolating the vane from the effects of surface side shear. This side shear acts on the cylindrical surface of the snow column produced during failure. The isolating ring also increased the ease with which weak interfaces were located and increased the rigidity and strength of the end vane.
- The split core sampler proved to be reliable in obtaining snow stratigraphy and density information. It could not be used for identifying snowpack weaknesses.
- The HydroSense soil moisture measuring system required calibration for each snow type and was not used as a measure of snow moisture content. No results were obtained for the Aquaflex soil moisture measuring system.

4.7 Conclusions

As a result of the two field studies carried out with this shear vane the following conclusions can be made regarding the end vane design characteristics.

1. The isolating ring is essential for the location of weak interfaces and to provide rigidity and strength to the end vane.

2. Vane height does not affect shear strength measurements of a tested layer however the ability to test within thin layers is reduced as vane height increases. A minimum vertical dimension is therefore desired. Ideally this dimension would be smaller than 5mm while having sufficient strength to be driven through hard ice layers without failure.

3. Shear vanes with a small cross sectional area (50cm^2) appeared to have shear strength measurements influenced by snow disturbance. Large vanes (250cm^2) on the other hand did not cause failure of the snow column before the maximum torque was reached and resulted in considerable transportation difficulties in the field. Therefore the ideal vane cross sectional area is expected to fall somewhere in between these values.

4. Some variation in measured results were observed for different shear loading rates. The significance of this effect is not known however it may be desirable to perform shear tests at a constant loading rate to ensure repeatability of results.

5. A method of cutting through hard snow to measure the shear strength of underlying layers is desirable.

6. A continuous measurement of snow shear strength is desirable so as to avoid missing critical, thin layers.

Chapter 5

Prototype Shear Penetrometer

This chapter provides a summary of the prototype shear penetrometer developed during the course of this research. The overall system requirements are firstly presented followed by each of the individual sensor modules, the signal transmission module and the test rig.

5.1 System Requirements

5.1.1 Introduction

Observation of snow safety personnel, a review of research literature and personal experience have highlighted numerous design features which must be incorporated into a snow stability instrument. Many previously developed devices have focussed on measuring snow properties that have no known relationship to snow slope stability and therefore serve little purpose other than satisfying scientific interest. Development of this shear penetrometer has therefore focussed on maintaining a close link between the properties being measured and the mechanical strength properties of alpine snow. This has been achieved by developing a multi-sensor device incorporating;

1. A shear vane.
2. A high resolution force penetrometer.
3. Two independent temperature sensors.

The shear vane has been the focus of this study and as a relatively untried measure of snow mechanical strength, has remained the instrument of interest. Force penetrometers on the other hand have had wide acceptance and use as a practical tool for obtaining snow profile information and represent the latest instrumentation developments within the field of snow science. Although not directly related to snow slope stability, force penetrometers provide considerable information regarding snowpack layering and have shown a good correlation with snow profile observations. Snowpack temperature, or more importantly temperature gradient is measured as it may identify the metamorphic processes occurring within specific regions of the snowpack and therefore provide an indicator of the changing nature of stability.

In addition to these measurement requirements the instrument must be highly portable, capable of measuring to the full depth of a seasonal snowpack, provide immediate snow stratigraphy information to the operator and incorporate suitable design features to ensure the integrity of the obtained measurements. A detailed description of the design features for each of the shear penetrometer components are presented within their respective sections later in this chapter.

5.1.2 System Components

The instrumentation system described in this chapter consists of three physically separate components; an instrument probe, a laptop/handheld computer (and receiver) unit and a test rig, as illustrated below in *Figure 5.1*.

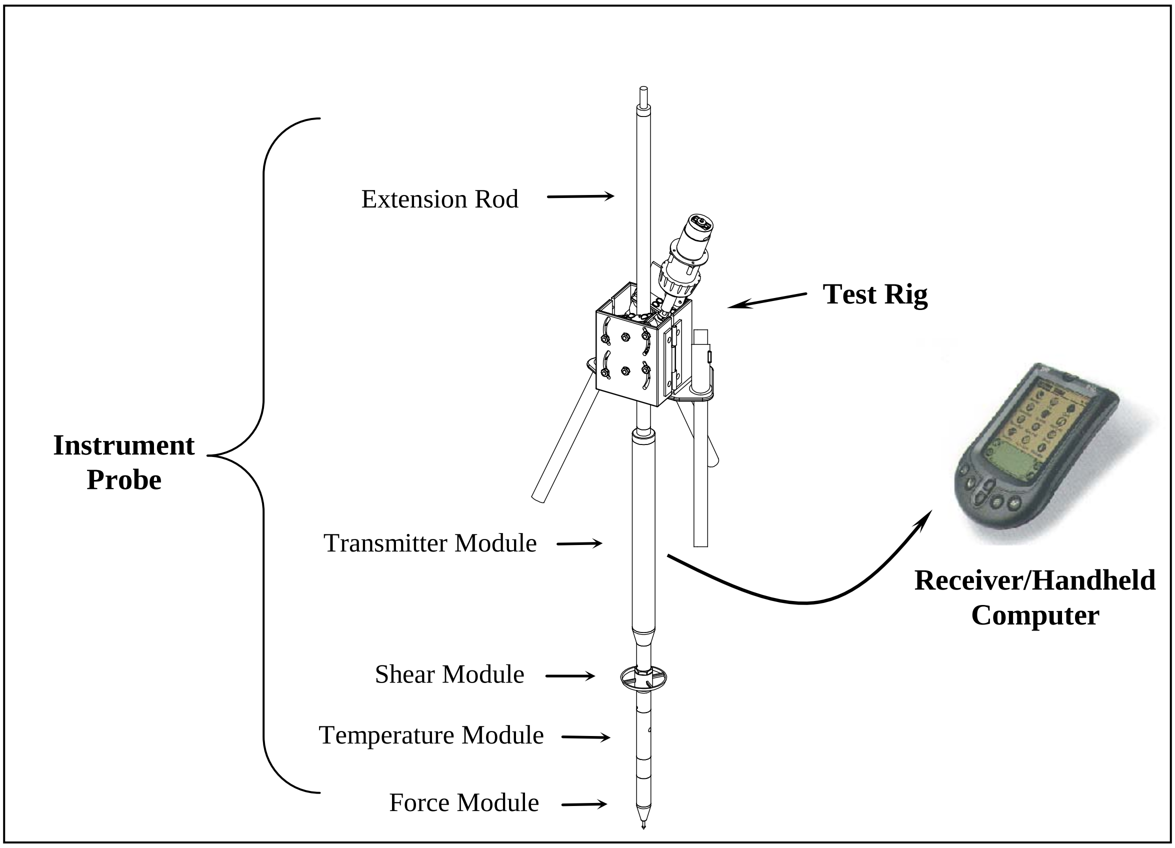


Figure 5.1: Shear Penetrometer System.

As shown in this diagram the instrument probe is made up of individual shear, temperature and force sensor modules as well as a signal transmission module and numerous extension rods. The number of extension rods to be used being dependent on the depth of the snowpack. Data from each of the sensor modules and a magnetometer contained within the transmitter module (used to measure rotations of the instrument probe and therefore infer depth measurement) is sent via radio link to a receiver and laptop/handheld computer above the snow surface.

The system developed during the course of this Master's research involved the use of a laptop computer for data collection. This data was received as a series of numerical values however it is anticipated further development of this system will include a graphical representation of the variation in measured properties with snowpack depth. It is anticipated a handheld computer will also be used.

The test rig is used to drive the instrument probe through the snowpack in a direction perpendicular to snow layering. It is held in position by three legs, pushed deep and at an angle into the snow, with the mechanical force to drive the instrument probe provided by an electric motor. The design of this device provides the instrument probe with simultaneous rotational and penetration motion with the ability to vary both the angular and translational speed.

5.1.3 System Electronics

The instrument probe electronics are summarised in the block diagram of *Figure 5.2* and consists of a main electronics control module (contained within the transmitter module of the instrument probe), that interfaces with the sensor transducers via a one wire serial bus. In operation the microcontroller collects data sequentially from each of the transducers which is then transmitted, via radio link, to the receiver unit above the snow surface.

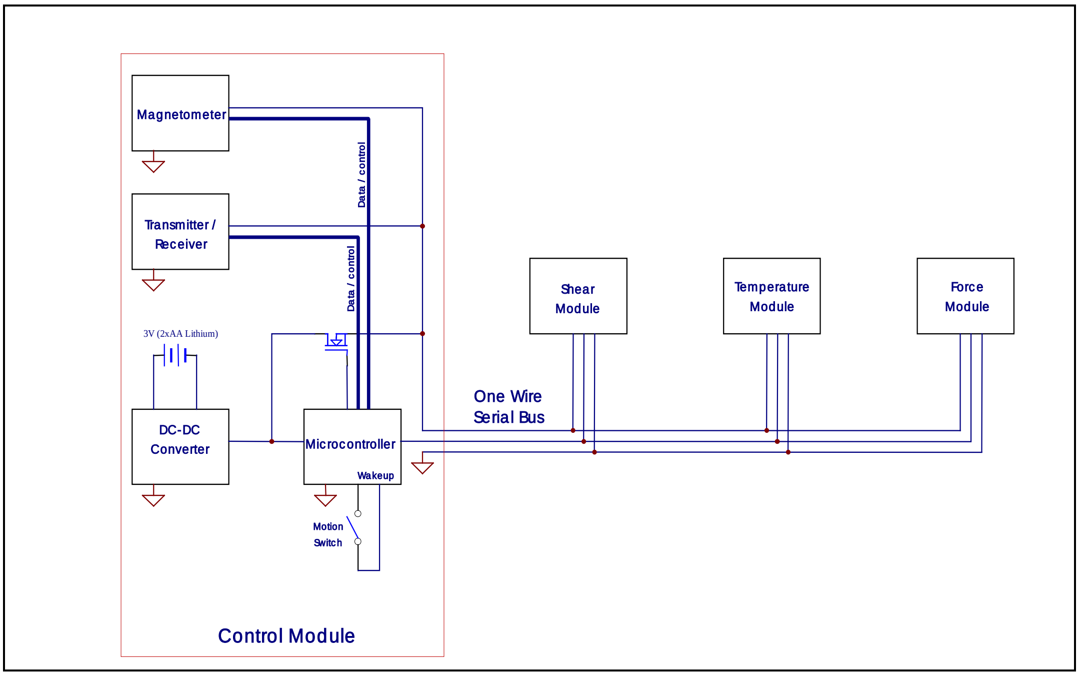


Figure 5.2: Shear Penetrometer Electronics Block Diagram.

The one wire serial bus protocol incorporated into the electronic design of this shear penetrometer allows for modular construction of each individual sensor. This provides flexibility in the number and type of sensor modules used at any one time and allows for the possibility of developing additional modules at a later date. Each of the sensor modules contains its own amplification and signal conversion circuitry contained on a small circuit board. 2.5mm 3 pole connectors provide the required electrical connections between each of the modules allowing the sensors to be separated without twisting internal wiring.

Power supply is in the form of 2 AA Lithium cells housed in a battery holder within the transmitter module. To conserve power the electronics control module will automatically enter into ‘sleep’ mode should the magnetometer fail to log a rotation for 255 consecutive samples. A gentle shake will activate a motion switch to ‘wake’ the device. Batteries are easily replaceable and have an expected life of 2 years while in ‘sleep’ mode.

5.2 Force Module

5.2.1 Literature Review

In practical use for almost fifty years the force penetrometer, in its various forms, has proven to be a popular and fundamental area of snow science research. The last decade in particular has seen a resurgence in snow force penetrometers due to advances in instrumentation and sensor technologies which have allowed the development of smaller devices with a greater number and variety of sensors.

Despite their recent popularity, force penetrometers when used solely for obtaining stratigraphic inference, have several fundamental difficulties. Firstly the critical layers in avalanche formation can typically be less than 1mm thick, with even the most advanced penetrometers failing to provide a vertical resolution better than 4mm. And secondly, although showing a good correlation to tensile strength in homogeneous artificial snow, (Gubler, 1975), there is no discernable relationship between the penetration force and the all-important snow shear strength.

The *Rammsonde* (also called the *Swiss Rammsonde* or *Haefeli Sonde*) was developed from penetrometers used in soil mechanics, incorporating a 60° included cone angle and a diameter of 40mm. Driven into the snowpack by the impact of a falling mass, the hardness of a snow layer is determined by the depth of penetration (Bader et al, 1954). To this day the rammsonde remains the only snow penetrometer to have wide practical acceptance and use.

A commercial soil penetrometer with a dynamic impact (hammering) was adapted to the original rammsonde (Navarre et al, 1994). This instrument shows a better spatial resolution because the depth measurement and energy-impact calculation are automatically processed, however the ability of the instrument to detect thin layers is again limited by the size of the cone.

The snow resistograph uses an upward working blade, providing a graphical output of the force required to raise the device through the snowpack (Bradley, 1966). Despite a good correlation between this instrument and the ram penetrometer and a much better resolution of weaker layers (St. Lawrence and Bradley, 1973), the snow resistograph has not been widely used.

Development of the digital resistograph saw a new level of technology applied to snow science research, with the electrical output from a load cell being recorded every 5mm (Dowd and Brown, 1986). A further development, (Brown and Birkeland, 1990), allowed the data to be downloaded to a computer, however the problem of vertical resolution was not resolved and this instrument suffered from poor durability.

A commercial geotechnical instrument was developed into a snow penetrometer with a cone diameter of 11.3mm and an included angle of 60° (Schaap and Föhn, 1987). The instrument showed a very fine resolution, especially for harder layers, some of which could not be located by traditional snow profile analysis. With a vertical cone dimension of 9.8mm the diameter is still too large to allow the detection of thin layers.

In order to measure numerous snow properties in one measurement the *Advanced Digital Snow Sonde* was developed (Abe et al, 1998). This instrument measured penetration force, electrical conductivity and optical reflectivity of both dry and wet snow samples, however the relationship between these properties and the mechanical strength of snow is largely unknown.

The most recent advances in snow force penetrometers have come with the combined effort of the Swiss Federal Institute for Snow and Avalanche Research and the U.S. Army Cold Regions Research and Engineering Laboratory. This research has brought about the introduction of the *SnowMicroPen,* a high resolution force penetrometer incorporating a small diameter (5mm) cone with a highly sensitive quartz piezoelectric force sensor. This device has shown a good correlation between both rammsonde measurements and snow profile observations (Schneebeli and Johnson, 1998).

5.2.2 Design Features

As a result of the extensive amount of research already carried out on snow force penetrometers the force module of this instrument was developed largely based on the existing SnowMicroPen design. The SnowMicroPen represents the latest in snow force penetrometer research incorporating much smaller measuring tip dimensions than other penetrometers and therefore providing a better resolution of thin layers within the snowpack. For this reason the *Measurement Tip* geometry of the new instrument was based on that of the SnowMicroPen.

The force transducer contained within the SnowMicroPen consists of a Kistler Type 9203 piezoelectric force sensor valued at NZ$2805. A much more economical transducer (*Honeywell FSG15B1A Force Sensor* valued at NZ$170) was selected for the shear penetrometer developed during this research. This transducer has a much smaller range of force measurement (0-15N compared to 0-500N for the Kistler Type 9203), however published SnowMicroPen data indicate all measured values are below 10N with critical layers typically having a penetration resistance less than 1N (Schneebeli, Pielmeiser and Johnson, 1998; Schneebeli and Johnson, 1998).

As a result of selecting a different force transducer much of the design of this module centred around incorporating the required internal componentry while minimising module size (diameter and length). The final design is illustrated below in *Figure 5.3.*

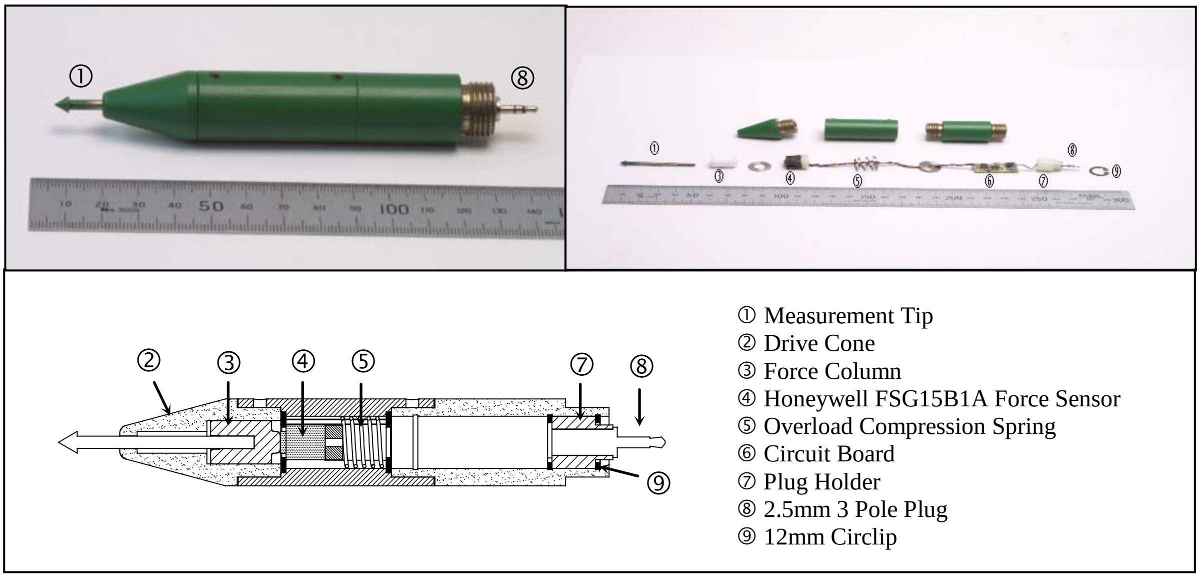


Figure 5.3: Force Module.

As previously mentioned the measurement tip is developed from the existing SnowMicroPen design with its main features being summarised below.

- Small vertical dimension (4.3mm) allows measurement of thin snowpack layers,
- 60° cone angle breaks snow grains apart rather than producing a compressive failure which would otherwise produce erroneous results,
- Flared tip reduces frictional effects of snow contact ensuring measurements are the result of forces acting solely on the measurement tip end cone,
- Protruding measurement tip from the *Drive Cone* reduces the snow disturbance influence caused by the much larger drive cone diameter,
- High rigidity to maintain measurement integrity.

The drive cone incorporates a small 30° angle in order to reduce the effect snow disturbance influences would have on measured force values. As the main probe body has a larger diameter than the measurement tip the snow is forced around it influencing the snow ahead. The small angle cone reduces this effect. The small external diameter of the drive cone and the entire force penetrometer (20mm) has the added effect of reducing the instrument weight as well as reducing the force required to drive the instrument probe through the snowpack.

The snow penetration force is transferred through the measurement tip and a sliding component (*Force Column*) to act against the Honeywell FSG15B1A Force Sensor. This force column is fabricated from Teflon which possesses a low coefficient of friction providing easy sliding within the drive cone. Overloading the force sensor causes the *Overload Compression Spring* to compress allowing the force column to bottom out on a stainless steel washer. This prevents damage to the sensor which has a maximum overload capacity of 55N.

The overall length of the force penetrometer is significantly affected by the length of the contained circuit board and considerable electrical design work centred around reducing this length. Having three individual segments to this module also increased the overall length, however this was necessary in order to assemble the device.

In order to ensure the 2.5mm electrical connectors, used throughout the entire instrument probe, maintain full contact it is necessary that the connecting plugs and sockets are accurately positioned. This is achieved by using a *Plug Holder* to centre the *2.5mm 3 Pole Plug* in the middle of the probe body with a *Circlip* fixing it in place.

All sensor modules and components of the signal transmission module were fabricated from austenitic stainless steel due to its non-magnetic properties. This was required so as not to affect the magnetometer measurements. A Teflon coating was used to prevent snow from freezing onto the surface of the instrument and influencing measurement values.

5.3 Temperature Module

5.3.1 Sensor Selection

When in operation, all sensor modules are constantly rotating about an axis perpendicular to snowpack layering while at the same time penetrating the snowpack. As a result of this constant movement an accurate measurement of temperature is very difficult to achieve. As previously discussed it is not so much the actual snowpack temperature that is of significance in snow stability work but the temperature gradient as this determines the dominant type of metamorphic process occurring and hence indicates whether the snowpack is gaining or losing strength. It is proposed that the use of a fast response temperature sensor, although unlikely to provide an accurate temperature measurement, will provide an indicator of relative temperatures within the snowpack.

Two independent ‘T Type’ thermocouples with internal cold junction compensation derived from a semiconductor temperature sensor were selected for this application. Thermocouples were chosen due to their small mass and therefore rapid response time. Resistance Temperature Detectors (RTD’s), thermistors and semiconductor temperature sensors were also considered for this application, however their relatively low response time saw them discounted in favour of the thermocouple. ‘T Type’ thermocouples were selected due to their linear characteristics in sub-zero temperatures.

5.3.2 Design Features

The final temperature module design is illustrated below in *Figure 5.4.* As shown in the photographs within this figure the thermocouple wires are of considerable length. This is for calibration purposes only, with the final working prototype to incorporate thermocouple wires just protruding from the module's casing.

As the external diameter of this module and the electrical connection requirements are already predetermined the mechanical design features are limited to the module length and thermocouple connections. Again considerable electronic design work was involved in reducing the circuit board length and included the placement of electronic components on both sides of the circuit board. Holes were included in the temperature module casing for the thermocouple wires. Plastic plugs were proposed to hold the final, much shorter, thermocouple wires in position, just contacting the snow surface.

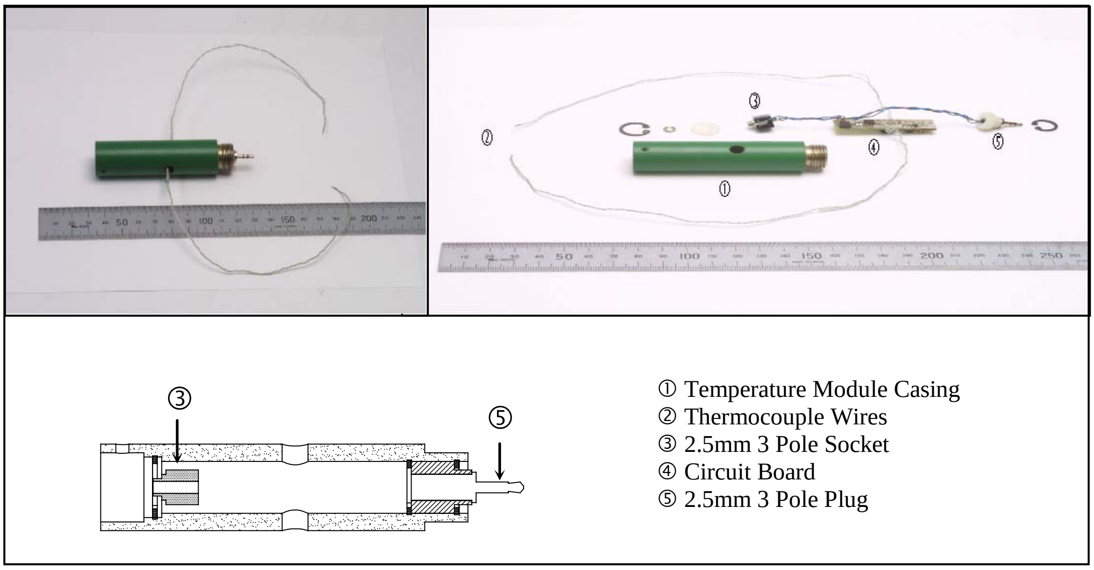


Figure 5.4: Temperature Module.

5.4 Shear Module

5.4.1 Torque Measurement

This Master's research has focussed on the measurement of snow shear strength with considerable field testing being carried out using a shear vane with various end vane configurations, as previously discussed in *Chapters 3* and *4*. The shear module of this instrument represents a new development of the shear vane providing an electrically measured value of the torque required to cause the shear failure of a snow sample.

The *Shear Vane* used in this instrument is supported in a bearing assembly allowing a small amount of 'free' rotation relative to the main instrument body. At the end of this motion a cantilevered beam (*Vane Carrier*, which is also 'free' to rotate), contacts a fixed member (*Hollow Bolt*) attached rigidly to the main body of the instrument probe. As a result of this contact, and the resisting torque required to prevent motion, the cantilevered beam undergoes slight bending. This is measured by small (2mm) foil strain gauges cemented to the beams surface. Through calibration these measured strain values will be used to determine failure torque and ultimately snow shear strength. This measurement method is illustrated below in *Figure 5.5*.

In order to incorporate an overload mechanism into this system the cantilevered beam was designed oversize so that it could endure the expected range of torque measurements without permanent deformation.

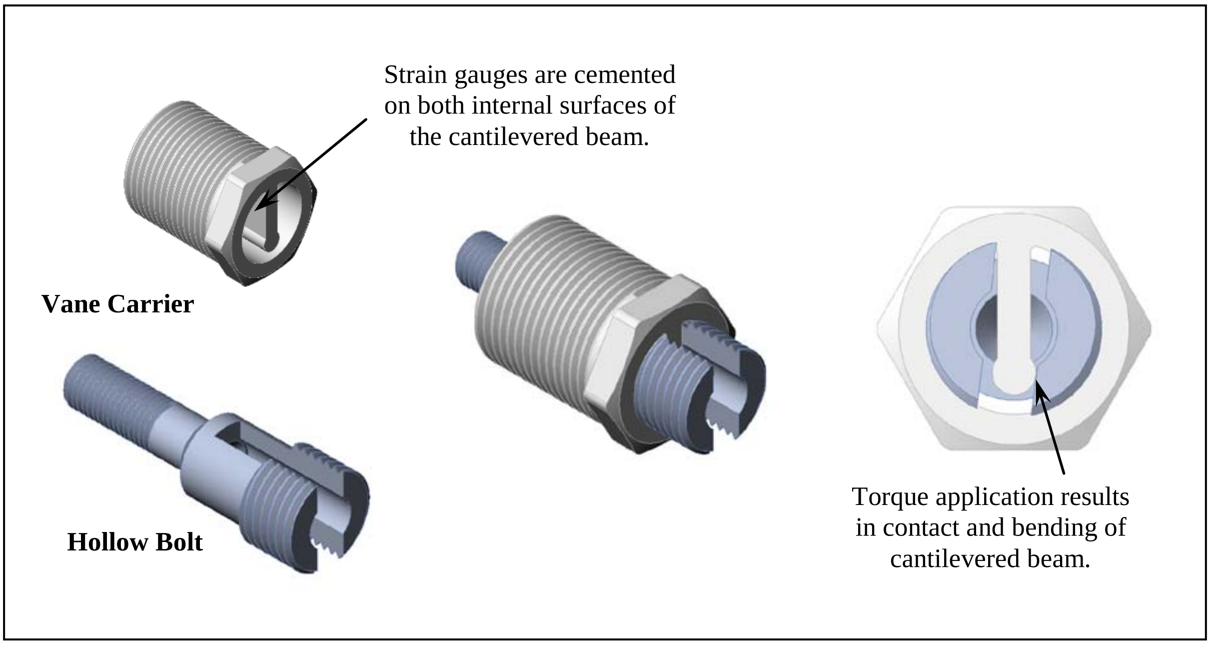


Figure 5.5: Torque Measurement.

5.4.2 Design Features

The main design challenge of the shear module was to firstly establish a reliable method of torque measurement and then secondly, to incorporate that measurement system into an instrument only 20mm in diameter. Many design iterations were carried out before the final configuration was established with the result being the development of a very compact, robust and relatively lightweight sensor module. This shear module incorporates numerous design features in order for it to carry out its intended function as an instrument for measuring snowpack properties. These features are summarised throughout this section and are illustrated below in *Figure 5.6*.

The shear vanes of this instrument are easily interchangeable and simply screw on/off without the need to remove any other components, even when the shear module is attached to the temperature and force penetration modules. Should the shear vane become difficult to remove (due to ‘freezing up’ or thread contamination) the hexagonal head of the vane carrier allows the module to be held in a tool while the vane is manually unscrewed.

Only one vane was fabricated for this prototype device, however it is likely that numerous shear vanes will be developed for various snow conditions. The fabricated vane incorporates a small vane height (5mm) reflecting the need to be able to measure thin snowpack layers. Additional features of the shear vane are it’s chamfered lower edges to reduce friction as the vane enters the snowpack and to aid in cutting through hard snow layers. The close tolerance between the shear vane and the *Bottom Casing* is also designed to limit the volume of snow able to force its way between these components.

Contained in a bearing assembly the shear vane, and more importantly the torque measurement system, is isolated from the effects of side loading. Two *Deep Groove Ball Bearings* allow the vane carrier to rotate freely however prevent the recording of erroneous measurements due to translational forces.

Much consideration also went into the assembly of this module with particular regard for the electronic requirements. Again the standard 2.5mm 3 pole electrical connectors were used to interface with the adjoining modules, with the use of several much smaller electrical connections integrated into the electronics circuitry within the sensor. This allowed the connecting sockets to be passed through various components allowing the module to be disassembled. Some parts however cannot easily be disassembled as wires are either soldered into position or cemented on the inside of various components to avoid contact of moving parts.

The shear vane and all external surfaces were coated in Teflon to reduce the effect of snow sticking/freezing to the instrument.

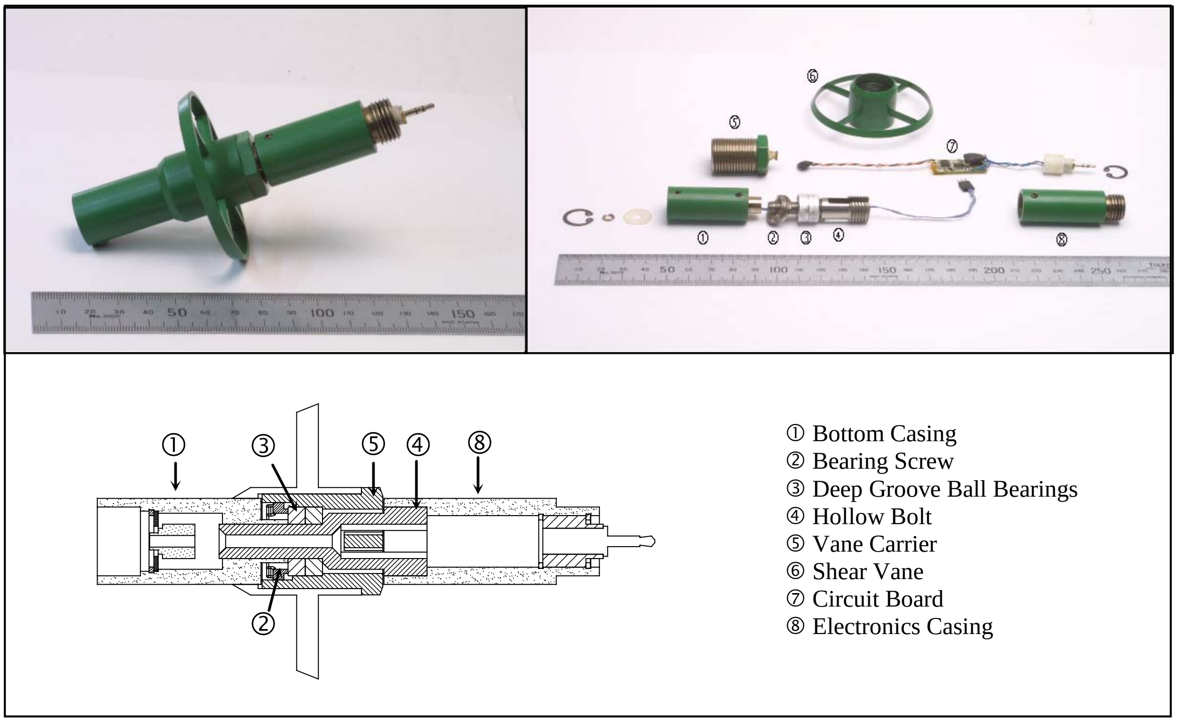


Figure 5.6: Shear Module.

5.5 Signal Transmission Module

The signal transmission module forms the electronic framework about which the instrument probe operates. It contains the microcontroller electronics, which interfaces with each of the individual sensor modules, as well as containing a transceiver unit which has the capacity to both transmit measured data and receive operating instructions via radio link. It also contains the instrument probes power supply in the form of two AA Lithium cells.

Shown in *Figure 5.7* the transparent Polycarbonate casing is clearly visible along with the respective mechanical connections to the shear module below (left) and to the instrument probe’s extension rods above (right). The microcontroller circuit board (with diagnostic Light

Emitting Diodes (LED's)), the transceiver circuit board and the battery holder are also evident in this photograph.

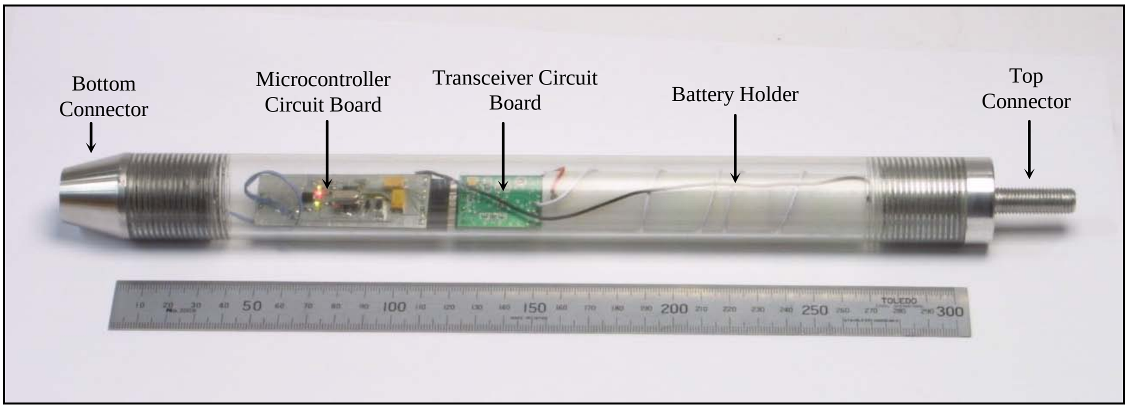


Figure 5.7: Signal Transmission Module.

The signal transmission module contains no moving parts and as a result the mechanical design of this module was relatively straightforward. The main design considerations consisted of;

1. An internal diameter sufficient to contain internal components (Minimum 22.5mm internal diameter for transceiver circuit board).
2. A sufficient length to contain the above mentioned components.
3. A non-magnetic casing so as not to affect magnetometer readings. Selecting a Polycarbonate casing had the added advantages of;
    - Allowing the radio signal to pass through the casing without the requirement of including special design features for this purpose.
    - Allowing the operator to visually inspect diagnostic LED's without disassembling the module.
4. Mechanical connections to match shear module below and extension rods above.
5. Electrical connections to interface with 2.5mm 3 Pole electrical connectors used throughout the instrument probe.
6. Cone angle to reduce friction while inserting instrument probe into snowpack.

5.6 Test Rig

5.6.1 Introduction

The test rig described in this section consists of a portable mechanism used to provide mechanical power to operate the shear penetrometer instrument probe. To fulfil this function the device must be highly portable, simple to operate and exhibit constant speed rotation and penetration characteristics. The developed test rig is shown below in *Figure 5.8*.

Spatial variation in snowpack properties is extremely diverse and requires testing to be carried out on slopes of varying aspect and elevation, often involving travel over considerable distances. Therefore, for this mechanism to be of practical use the test rig must be of lightweight construction and compact enough to fit into a backpack. Snow stability work can be an arduous task, taking place in the early hours of the morning often in adverse weather conditions. For this reason the device should be simple to operate and take little time to set-up. Additionally snow properties have been shown to exhibit a high strain-rate dependence and therefore it is highly desirable to maintain constant rotation and penetration speeds during the test procedure.

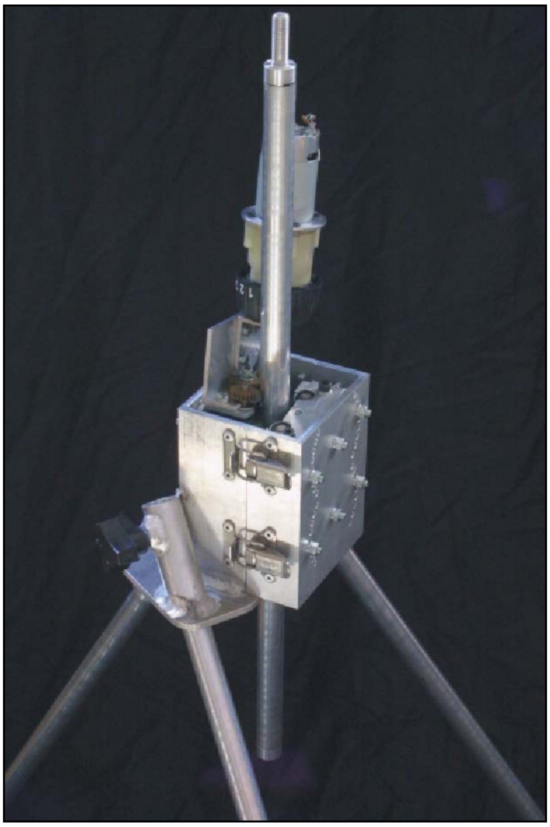


Figure 5.8: Test Rig.

5.6.2 Drive Mechanism

The test rig drive mechanism consists of a series of rubber rollers (8 in total) clamped firmly around the instrument probe's extension rods. The rollers are fixed in position at an angle offset from horizontal. This set-up provides a simultaneous rotation and translational motion of the extension rod with the relative amounts of each movement determined by the roller angle. This roller angle can be varied from purely rotational movement, occurring in the horizontal (0˚) position, through to a maximum translational movement occurring at 36˚ (physical constraint of this design). This drive mechanism is illustrated in *Figure 5.9.*

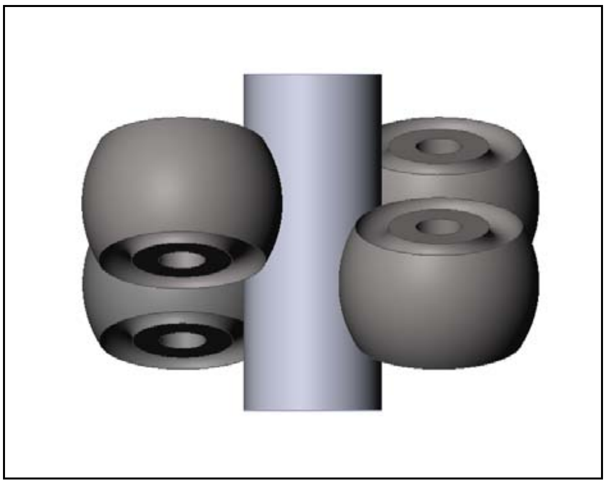


Figure 5.9: Test Rig Drive Mechanism.

Using this arrangement two of the rollers are coupled to a 14.4V DC motor to provide the mechanical force to rotate and drive the instrument probe down through the snowpack. The remaining 6 rollers are free to rotate and serve to maintain the instrument probe in an upright position as well as maintaining the direction of motion.

5.6.3 Test Rig Operation

This test rig is fixed into the snowpack using three tubular aluminium legs. These penetrate at an outward angle so that when fixed in position they resist the upward reaction force exerted on them as the instrument probe is forced down through the snow.

Operating the test rig first requires these legs to be arranged so that the instrument probe penetrates perpendicular to snowpack layering. Some traditional force penetrometers are required to be inserted vertically in the snowpack however this will result in shear measurements being taken in a plane other than in the expected snowpack shear failure plane.

The release of two toggle latches will then allow the front of the test rig to pivot open. The instrument probe can then be inserted into position within the rubber rollers and locked in place by refastening the latches. This provides a significant clamping force between the rollers and the extension rod, a force that is essential to prevent slippage between the components. The electric motor is then operated by holding down one of two electrical controls, each representing a different motor speed. This causes the instrument probe to rotate and penetrate the snowpack, transmitting sensor information back to a handheld computer as it does so. The test rig can then be removed and the instrument probe pulled from the snow manually.

5.7 Discussion

The shear penetrometer presented in this chapter is a new development within the field of snow science and as such, offers many potential advantages over present snow stability evaluation methods. Currently this device is untested and therefore much of the discussion in this section deals with potential difficulties with the developed device.

At present the ability of the temperature sensor to provide useful information is unknown. Field testing may reveal that the thermal response time of this sensor is insufficient to determine a reliable temperature gradient profile within the snowpack, due to the constant motion of the instrument probe. If this were found to be the case future testing and developments would therefore exclude this module.

The shear module represents the most significant and exciting development within this instrument. The significance of using a continuous shear measurement system is unknown but it is thought that this will provide the best opportunity for locating weak layers within the snowpack. These could otherwise be missed in a stepwise testing scenario.

The signal transmission module has been tested in sub-zero conditions and proved to function as required provided the contained circuit board was kept free of condensation. This is to be achieved by sealing all electronic components in wax prior to field testing. The radio transmitter has shown the ability to function over a considerable distance as well as through a volume of crushed ice. The ability to transmit through several meters of snow however is not known.

The test rig represents the greatest difficulties within the established system. As a result of the large diameter of the signal transmission module (due to transceiver circuit board requirements) the test rig is required to stand a long way off the snow surface in order to sample the entire snowpack. This requires long legs to hold it in place and is, at present, a relatively unstable platform for testing. This is especially evident on steep terrain where the weight of the test rig and instrument probe act to topple the device down the slope. The considerable weight and bulk of this device represent additional difficulties with the present design.

Despite the difficulties outlined above, the developed system offers the opportunity for field testing of this prototype instrument. From these results the working of the individual sensors and the interaction of the major system components will be assessed in greater detail. Additional prototypes will refine the present design of this instrument.

Chapter 6

Conclusion

The aim of this Master's study was to develop a portable instrument to provide rapid, quantitative snow stability information over the area of an avalanche start zone. This objective has been achieved to the extent that a prototype instrument has been designed and fabricated. All major system components (the instrument probe, laptop/receiver unit and test rig) are presently operational however no substantial field-testing has been carried out with this device to date.

The developed instrument offers many potential advantages over traditional snow stability analysis with the ability to provide rapid snow stratigraphy information over a large geographical area. Many potential difficulties also exist due to the untested nature of this instrument.

Work is continuing on the development of this device including computer programming of the operator interface, field-testing of the prototype instrument and the development of new sensor modules.

Chapter 7

Recommendations

The prototype shear penetrometer designed and fabricated during the course of this Master's research is the subject of continued development within the University of Canterbury. The recommendations contained in this chapter represent the author's opinion on the best direction these developments should take. These are summarised as follows;

1. Development of the operator interface incorporating a graphical representation of measurement values and how these values vary with snowpack depth. To provide a compact, portable unit this development should include the use of a handheld computer.
2. Drive mechanism development.
3. Fabrication of shear vanes of various dimensions and shapes.
4. Development of additional sensor modules. This could include;
    - Measurement of snow side friction.
    - Measurement of snow liquid water content

At present the measured data is printed directly to a computer screen during testing. This is adequate to prove the functioning of the individual sensors, however in order to be useful as a practical tool it is essential that the operator obtains an immediate indicator of snow slope stability. This information should therefore be presented in an easily interpreted manner in a time-span close to real time.

As a result of the considerable distances travelled in order to establish an accurate snow stability evaluation, it is desirable to keep the system size and weight to a minimum. A handheld computer is therefore recommended as a replacement to the existing laptop.

Despite the difficulties with the present test rig arrangement (*Section 5.7*), it is recommended that this system be maintained until the significance of variations in penetration and rotation speeds can be determined. If it is found that these speeds have little effect on measured shear strength values the drive mechanism could be replaced with a simple drill incorporating a manual (forced) penetration. Alternatively if a significant effect was observed several options could be considered for the development of this component. Firstly the external diameter of the signal transmission module could be reduced (to the 20mm external diameter of the probe body) allowing the test rig to attach at a much lower point on the instrument probe. Secondly, the test rig could be replaced with a completely different drive mechanism, attaching in a manner so as to overcome the height difficulties experienced with the present device.

The fabrication of shear vanes of various dimension and shape would be useful for measuring in different snow conditions. Vanes with small vertical dimensions may also prove a better identifier of thin snowpack layers. Shear vanes could also be designed that extend down the outside of the instrument probe. This would allow shear measurements to be taken closer to the bottom of the snowpack, without the need to remove the force penetration module.

Developed in modular form the present instrument probe allows the inclusion of additional sensor modules. Two potentially beneficial sensor modules would be the measurement of the side friction as snow passes the outside of the instrument probe and the measurement of snow liquid water content (particularly useful in New Zealand's maritime snow climate). Side friction is typically measured in geotechnical applications, in conjunction with a force penetrometer, to determine soil properties. This may provide additional information regarding snowpack structure and grain bonding characteristics. Development of a sensor module to measure snow liquid water content is currently the subject of a project in the Department of Electrical and Electronic Engineering within the University of Canterbury.

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Chapter 8

Appendices